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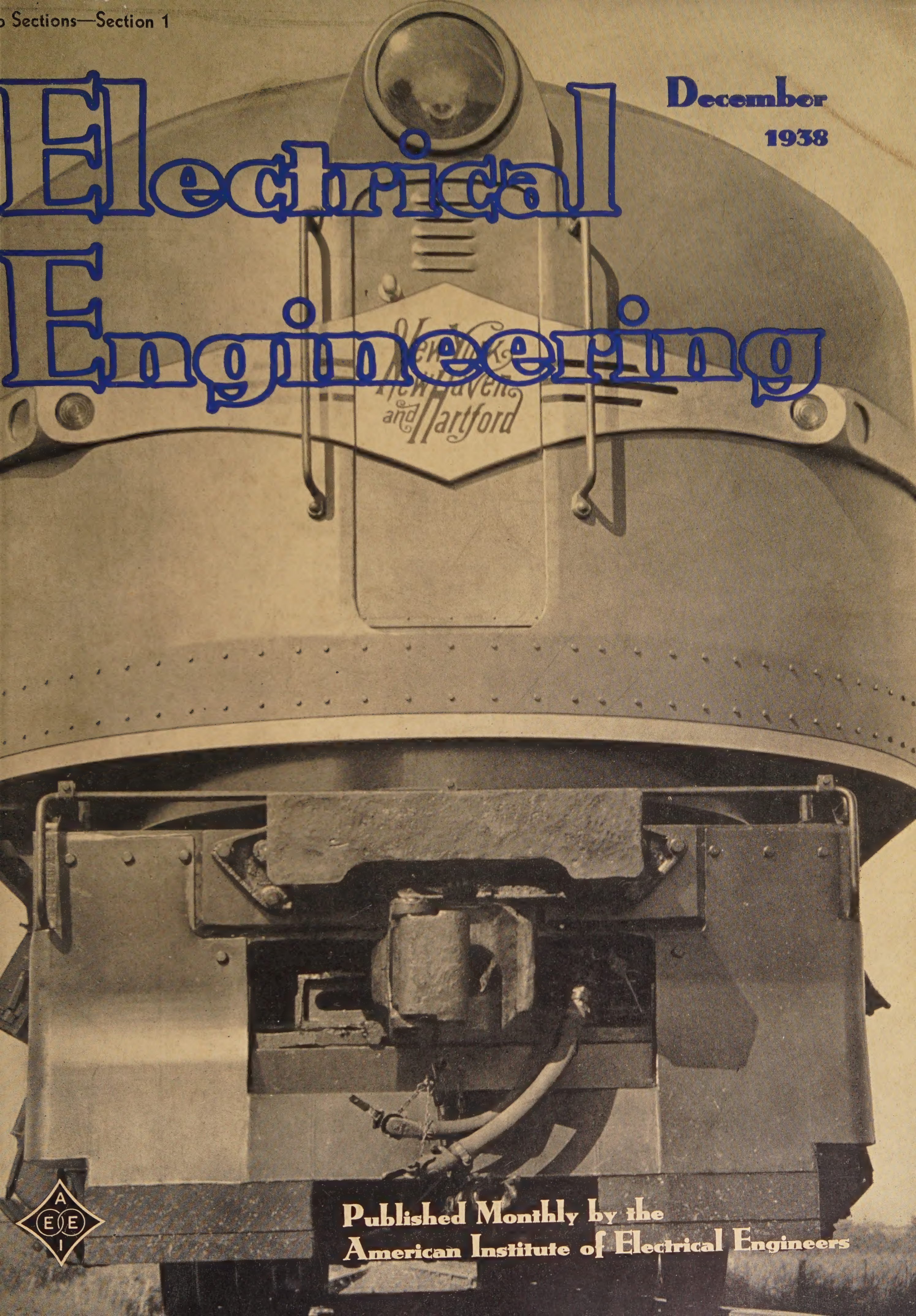
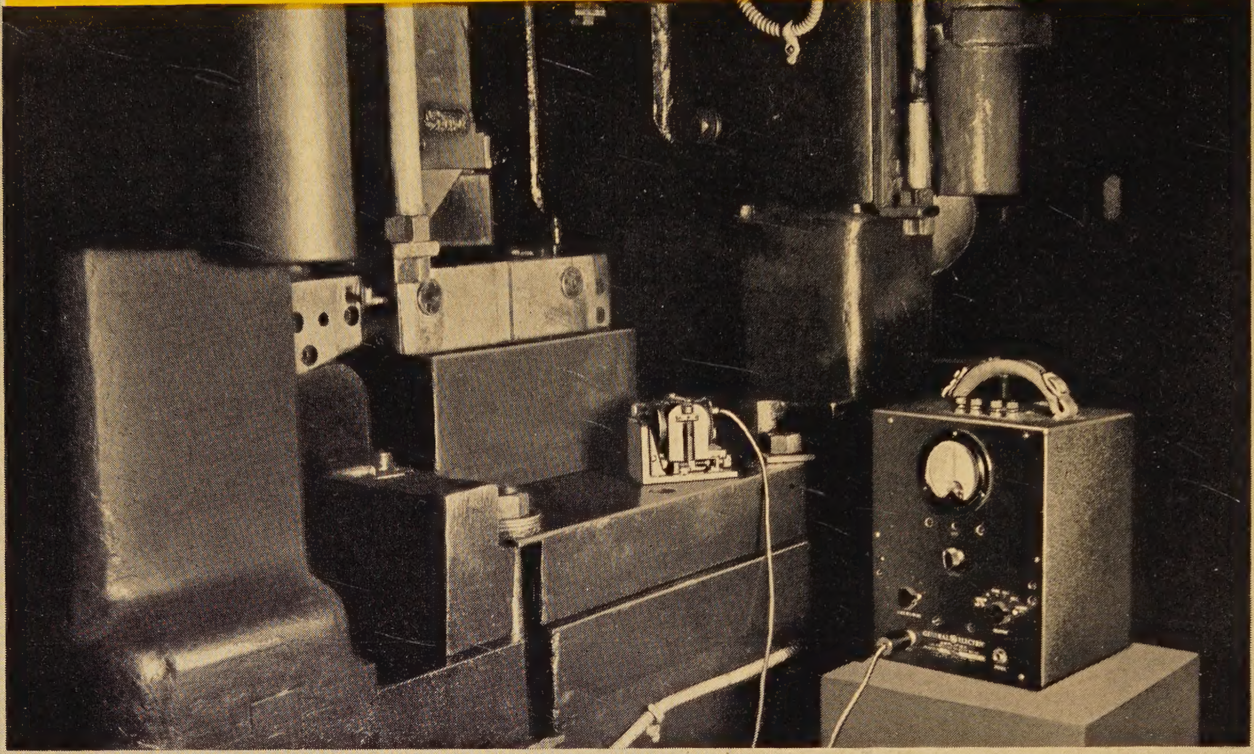
Electrical Engineering

December
1938



Published Monthly by the
American Institute of Electrical Engineers

To Measure—VIBRATION ELECTRICALLY



Measuring vibration of large punch press

VIBRATION is that pulsing, throbbing motion with which you are familiar—in machinery, in office buildings, even in a house. Seldom can you see it; more often only the finest sense of touch can detect the vibrating movement.

But suppose an engineer wants to know the amplitude of vibration, or the speed of vibration—that is, the vibration velocity—or the rate at which the velocity changes; i.e., acceleration.

An instrument recently developed by General Electric measurement engineers can measure these values accurately and either indicate or record them. It has been used to check motors in a production line, to study the vibration of turbines, fans, automobiles, buildings, and balancing machines, and for other applications. Such knowledge is valuable to the designer and will prove more and more so in view of the increasing importance of vibration in present-day industrial problems.

Thus, electricity continues to contribute to the progress of measurement—and in this work G-E engineers have played prominent roles. Today there are G-E instruments to measure color, sound, light, distance, lightning, and other phenomena. For electrical measurement, there are instruments to measure current, voltage, resistance, watts, frequency, power-factor — dozens of standard types, indicating and recording, in ratings to meet every need. If you have any problem that involves measurements, let General Electric, Schenectady, N. Y., help you solve it.

HEADQUARTERS FOR ELECTRICAL MEASUREMENT

GENERAL ELECTRIC

430-85

Electrical Engineering

Registered U. S. Patent Office

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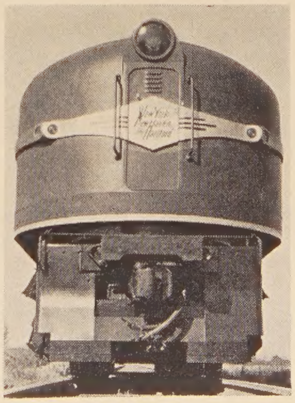
The Cover

One of the new 3,600-horsepower electric locomotives of the New York, New Haven and Hartford Railroad. Total weight is 432,000 pounds; total length, 77 feet

General Electric photo



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High Lights

1938 Reference Index. For the convenience of members and readers, the annual multi-entry reference index to material published by the AIEE during the year 1938 is published in pamphlet form as Section 2 of this issue of Electrical Engineering. As an added convenience, this index is divided into two parts: Part one covers general-interest articles and news items; part two covers all technical papers and discussions published in the 1938 Transactions, including both those preprinted in the monthly sections of Electrical Engineering and those published only in the Transactions volume, which are being reprinted in the "Transactions Supplement." Thus, those who have ordered copies of the Supplement will find all papers contained in that publication listed in this index.

Circuit Breakers. A new multibreak interrupter that is applicable to conventional tank-type high-voltage oil circuit breakers has a pressure-generating gap associated with each interrupting gap to force oil between the parting contacts (*Transactions pages 705–12*). To determine whether a 138-kv oil circuit breaker would perform successfully under severe duty on a system of high capacity, a series of field tests has been conducted on a large power system (*Transactions pages 696–705*).

Engineering and the Law. Many new legal problems have arisen out of the new developments in the social structure brought about by engineering and scientific achievements. While today engineers assist lawyers materially in situations where engineering questions are involved, there is an opportunity for broader service through a closer co-operation between the engineering and legal professions (*pages 477–9*).

Characteristics of Triodes. If vacuum tubes be operated with their grids strongly positive during a short interval in each cycle, the usual equation for plate current, used for negative or low positive grid potentials, is not valid for large positive grid potentials, but may be modified to produce dependable results (*Transactions pages 693–6*).

Remote Control. Omission of the customary master relays, phasing relays, and associated current transformers from network protectors in a low-voltage a-c network, and substitution of a remote-control system of pilot wires operated from relays at the supply substation, may provide a reliable installation at economical cost (*Transactions pages 685–92*).

Value of AIEE to the Engineer. "The Institute will realize its fullest value to the membership when as many as possible of the 15,000 members are participating in some way or other in the conduct of their professional organization" said AIEE President John C. Parker in an address at a recent Section meeting (*pages 506–07*).

Petersen Coils. Careful analysis of the characteristics of a power system has been found to be necessary before applying Petersen coils, which are intended to reduce outages by extinguishing the arc at the point of fault without the operation of circuit breakers (*Transactions pages 663–76*).

Fluorescence. A property of many substances, fluorescence consists of an emission of light under excitation by radiation of a wave length within a critical absorption band, and is associated with the presence of a specific ingredient at low concentration (*Transactions pages 677–81*).

Glass Insulation. Fiber glass now has been developed to the point where it can be woven into tape for insulating the windings of electrical machines. Its ability to withstand high temperatures makes it particularly adaptable to use in railway motors (*pages 480–3*).

Lightning. During the past four summers, lightning strokes to the 1,250-foot Empire State Building in New York, N. Y., have been studied, and many records have been obtained by means of the Boys (moving lens) camera and cathode-ray and crater-lamp oscillographs (*pages 493–505*).

Research and Progress. Continued research and development is necessary for technical progress, as is proved by the mortality of business enterprises not engaging in research whose products are permitted to fall behind and become obsolete (*pages 484–8*).

Memory Attachment for Oscilloscope. For obtaining oscillograms of "random phenomena and events immediately preceding and following their occurrence" a device known as the "memnoscope" has been produced (*Transactions pages 682–5*).

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Winter Convention. Two general sessions with speakers of national repute and technical sessions on a wide variety of subjects are being scheduled for the AIEE 1939 winter convention to be held in New York, N. Y., January 23–27 (*pages 508–09*).

Chemistry and Dielectrics. The chemist, as well as the engineer and physicist, has an important role to be played in the successful solution of problems in high-voltage dielectric engineering (*pages 489–92*).

Correction. In the article "Graphics in the Solution of Complex Quantities" by E. C. Goodale in the November 1938 issue, sentences three and four of paragraph one, page 453, should read: "The electrical quantities of a series circuit are determined most simply by finding first the impedances of the parts that are in series, then solving for the common *current* (if it is not given) and for the voltage drops. A multiple circuit is solved most simply by expressing it in terms of its admittances, then solving for the *common voltage* (*if it is not given*) *and for the* currents in the branches." The beginning of the third paragraph in the second column should read: "From the similar triangles OUB and OAB';" and the end of the first paragraph on page 454 should read: "From the similar triangles OAB and OUB'."

Coming Soon. Among special articles and technical papers now undergoing preparation for early publication are: two articles on the professional phase of engineering education—one discussing the subject from the viewpoint of professional registration, by P. H. Daggett (A'08) and the second presenting an industrial viewpoint, by O. W. Eshbach (F'37); articles based upon two papers presented at the Seventh International Management Congress—one on management's responsibilities to society, by A. W. Robertson (A'27) and the other discussing the influence of technical progress upon social developments, by K. T. Compton (F'31); an article reviewing the year's progress in insulation research, by J. B. Whitehead (F'12); an article presenting a summary of recent actions pertaining to the meter-kilogram-second (Giorgi) system of units, by A. E. Kennelly (HM'33); a paper on traveling waves initiated by switching by L. V. Bewley (M'37); five papers on the co-ordination of mathematics, physics, and electrical engineering subjects in engineering schools, by J. M. Bryant (M'13), W. A. Curry (F'37), M. G. Malti (M'34), T. H. Morgan (M'31), and B. R. Teare, Jr. (M'36); a paper on the application of capacitance potential devices by J. E. Clem (M'30); a paper on the flashover characteristics of transformer capacitor bushings by H. L. Cole (M'21); and a paper describing a current-limiting power fuse by D. C. Prince (F'26) and E. A. Williams, Jr. (A'37).

Statements and opinions given in articles and papers appearing in Electrical Engineering are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ Electrical Engineering is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index;* abstracted monthly by *Science Abstracts* (London). ¶ Copyright 1938 by the American Institute of Electrical Engineers. Number of copies this issue 22,100.

Engineering and the Law

By CHARLES W. APPLETON

New developments in the social structure, brought about by the results of scientific and engineering achievements, have increased the intricacy of legal problems tremendously. By working together, the lawyer and the engineer undoubtedly can contribute more than they have in the past through wider appreciation of the economic and social problems involved.

IN THE OLD DAYS a lawyer's business consisted largely of writing deeds, running down titles, making and breaking wills, convicting horse thieves, and bringing lawsuits about line fences. But how things have changed, with the improvements in the steam engine beginning with Sickles' drop-cut-off or detachable valve-gear, the growth of rail transportation, the expansion of the steel and textile industries, and the advent only yesterday of the steam turbine, automobile, airplane, and radio—all engineering creations—to say nothing of the dynamo and the motor, electric traction, elevated railways, electrified subways, and the great public utility companies.

It is notorious that during the heyday of this development, the legal profession flourished like a green bay tree. Think of the damage and injunction suits, condemnation proceedings, franchise disputes, railroad collisions, industrial accidents, and lawsuits arising out of contamination of the air and water. The disputes became so numerous and often the dockets of the courts were so clogged that the legislatures had to come to their relief and establish special machinery to take up the overload so that they might again function at their rated capacity.

There is a general impression that the law and the legal profession, and *not* engineering, is at the bottom of most of the annoyances and unpleasantness that afflict us, but I think that this idea comes from a failure to understand what the law really is. I am speaking, of course, of the common law inherited from England, which is rather figuratively spoken of as having been brought over on the Mayflower, and is in truth the glass in which democracy sees its feature and its form. The common law and the democratic institutions are as warp and woof, and a change in one has its inevitable repercussions on the other. Wrought for almost a thousand years as on an anvil out of the experience of the English-speaking people, recorded in countless books of law reports containing the printed record of millions of actual court decisions, it expanded step by step to attempt to adjust and reconcile and, as it were, to absorb and digest the new problems created by the rise of the scientific age. Dealing thus with the outburst of invention, the startling expansion of engineering applications, the introduction of the factory system, the dislocation of the domestic economy, and the bewildering increase in the complexity of social relations, it forms a heritage, the like of which is possessed by no other nation on earth.

One can think of law as an engineer or scientist thinks of electrons, atoms, molecules, attractions and repulsions, strains and stresses, masses. The individual is the electron; the atom the family; the molecule the corporation, association, village, or other small organized group; the masses the city, state, and similar large administrative divisions. The attractions and repulsions, the strains and stresses, the interrelations, the valences, as it were, are the rights and duties that law is designed to measure, evaluate, weigh, and enforce.

There have been innumerable definitions of "law," and thousands of books have been written on the subject. This arises from the fact that it is a general term and in its broadest sense means a rule or principle of action or reaction and may embrace anything from the laws of physics and chemistry or of the universe, to the moral law, the Roman or civil law, or so-called natural law.

Law in the sense that I am using it is the law that faces one when he is arrested or becomes involved in a lawsuit, and which is administered by the judges and juries sitting in the imposing court houses that may be seen in every county and city in the land.

The court decisions or "cases" may be taken as borings or samplings from a mine of experience of incomparable richness. They are all classified, arranged, and pigeonholed so that any trained lawyer can refer to them on the shortest notice. Many of the strange words and phrases in deeds and formal documents are actually inheritances and survivals from these ancient times. Many jokes have been built on the idea that lawyers are the slaves of precedent, but what would engineers, what would any learned body give if they had a written record of as many tests! And perhaps lawyers are not alone in being creatures of habit—only frank enough to admit it.

Now I am afraid that the conception of law entertained by engineers and many others is quite different, because in their daily work they are more likely to find themselves annoyed or thwarted as by the provisions of a city ordinance, regulation, or state statute, providing for inspection or the approval of a board, and they stand aghast at the flood of new statutes enacted annually by the states and the Federal Government. Well, the courts and lawyers must recognize these just as all other groups and citizens

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Essential substance of an address presented at a meeting of the AIEE New York Section, October 19, 1938.

CHARLES W. APPLETON is vice-president of the General Electric Company, New York, N. Y. He received the degrees of bachelor of science from St. Lawrence University (1897) bachelor of laws from New York Law School (1899) and doctor of laws from St. Lawrence (1929). After several years of private law practice in New York, N. Y., he was successively assistant district attorney, New York County, 1903–10; instructor, Brooklyn Law School, 1909–18; city magistrate, New York, 1910–18. He became counsel of the General Electric Company in 1918 and was elected a vice-president in 1927.

do, but the lawyer thinks of them as *laws* and not as law. They are the result of action by the legislative and not the judicial branch of the government, but may come before the courts for interpretation either as to their meaning or their conformity to the basic law of the land.

Numerous as these laws seem to be, they are after all a mere fringe on the body of the law and in many instances are made necessary to deal with situations to which the processes of litigation often are unsuited or inadequate because of the suddenness or rapidity of the social changes created by engineering and scientific developments. But under and above it all is that great fundamental "law of the land," recognition of which by King John was compelled by the barons in Magna Charta in 1215, and which has been defined better than anywhere else by Daniel Webster in his argument in the famous Dartmouth College case where the New Hampshire legislature, without its consent, had attempted to alter the charter of the corporation granted to it by the British Crown. "By the law of the land," said Webster, "is more clearly intended the general law, a law which hears before it condemns; which proceeds upon inquiry, and renders judgment only after trial. The meaning is that every citizen shall hold his life, liberty, property and immunities, under the protection of the general rules which govern society." Not every enactment or statute passed by the legislature, not all "laws," said he, are *law* unless they conform to the fundamental law of the land, and in this case the charter was a contract that could not be impaired and that even the American revolution had not dissolved.

Now what are the methods, what is the technique of the law? Manifestly as new developments in the social structure, in science, invention, and engineering are brought before the courts, they cannot rely on the precedents because the force or apparatus is an entirely new one or is given a new application. Naturally questions arising in connection with them never before have come to the courts for adjudication. Therefore, no other course is left but the resort to analogy in an attempt to find a guiding principle.

Let me illustrate how they dealt with electrical phenomena. Of course, only scientists and engineers knew what electricity was in 1779 when Volta discovered that it flowed, or when in 1825 Sturgeon found he could make an electromagnet, or when in 1831 Faraday made the first dynamo, and Edison later established his central station, or when Stanley came along with his transformer in 1886, the year in which a whole galaxy of engineers rose above the horizon like the sun in its chariot and the a-c era began.

Out of a clear sky, as it were, a multitude of legal problems arising out of this fearful progeny of the thunder cloud were laid at the door of the courts—mysterious forces that disturbed the telegraph and telephone, that gnawed at the service pipes and iron structures, that disturbed the electric lights. What were they? Was priority to control? Was first in time, first in right, according to the old maxim? If adjustments were possible, should they be compelled, and if so, who was to make them, and how was the expense to be apportioned? Could any one do as he pleased on his land so long as he was skilled in his art, or did he act at his peril if his neighbors were injured or annoyed? Heretofore the owner of the surface had owned from the center of the earth to the top of the sky. As an early lawyer who was used to calling a spade a spade expressed it: "He who owns the soil owns all above and below from heaven to hell." The land law which grew out of the feudal system was the most ancient, the most certain, the most unalterable of any part of the common law. The highways were laid out for passage and travel on foot or horseback, possibly with horse and buggy.

Lawyers and courts turned to the nearest analogy. If one gathered water on his land in unnatural quantities, as by a reservoir and it escaped to the injury of another, it had been held that he was liable in damages. If he harbored a vicious animal and allowed it to escape, again he was liable. If even on his own premises he created a noise that disturbed his neighbors, or poured noxious fumes into the air, or polluted the common stream, again he must respond in damages to those who suffered from his acts. While it was conceded that one might do what he would with his own, there was a corollary to this to the effect that he must do so without injuring another who had rights of his own. With some such reasoning, the courts approached problems of electrolysis, of inductive interference, and are today wrestling with radio interferences as related to the use of diathermy apparatus; and before long we may prophesy X-ray and ultraviolet insulators and other electrical phenomena and devices.

The development of aviation and broadcasting present two other areas of conflict. By the old law, the owner of the surface had the rights to which I have referred. But the law does not indulge in theory, and when a real case arose the plaintiff had to show that he suffered damage or that the person using the air had created a nuisance, and this he was seldom able to do. Since airplanes covered such vast distances in so short a time, and courts as a rule could function over only limited areas, prevention rather than post mortems appeared to be in the public's interest. Therefore, Congress passed a statute regulating air traffic and empowering the Secretary of Commerce to formulate rules dealing with the altitude above the earth that the pilot must follow and other matters. While it may seem that this made a change in the law, as a matter of fact the legislative act is merely an attempt to reduce the hazards, to minimize litigation, and facilitate the growth of the art. Again, the new legal problems growing out of broadcasting are staggering in their import, with their effect on the freedom of speech, liberty of the press, and even international relations. These problems today stand at the door of the courts; and we may be sure that through the due processes of the law of the land, supplemented and augmented here and there by legislation, their solution at last will be found. But this is not the end. There will be no end until, in the words of Kipling, "earth's last picture is painted."

Need we ask how the courts will approach the problem of the stratoplane when it begins to interfere with the ancient art of flying in the nether air and to crowd the regular users from the landing fields? Wasn't the air made to fly in, just as the streets and highways were laid out to walk on or travel on with horse and buggy?

What a wonderful thing it would have been if earlier in this period of development lawyers and engineers could have had a better understanding of each other's problems and had worked closer together to anticipate their solution on a basis that would command public support, having regard to the daily increase in the complexities of social relations and the consequent problems of legislation and government. Then we might have had less public regulation and more self-regulation, fewer entangling ordinances and battalions of inspectors, and a lesser flood of legislation.

The work of the Joint Subcommittee on Development and Research of the Edison Electric Institute and Bell Telephone System composed of eminent lawyers, executives, and engineers and dealing with physical relations between electrical-supply and signal systems is a striking example of what might have been accomplished. It is "too late to cry over spilled milk," but it is not too late to look ahead to the end that we may profit by the experience of the past as we approach the problems that lie ahead. As in the past, I believe that the burden will continue to rest upon what seem to me to be the great pillars of our social and economic system—engineering and the law.

There was a time when men of good intellectual and moral parts, like Washington, Jefferson, and Franklin, could comprehend, and as it were, encompass the phenomena of the times in which they lived and give them direction. But granted that we have men with equal intellectual power and love of country today, how enormously more difficult is the task with all the new forces and developments to which science, engineering, manufacturing, and methods of distribution have given birth.

Today we are floundering in a morass of uncertainty in so many directions just because, as it seems to me, we are "a prey to economic illusions," in the language of Justice Holmes, and are afraid to look facts in the face. Courts that are untrained and inexperienced in business and economics attempt to adjudicate problems of business and economics. Doctors of philosophy and economists attempt to deal with law who do not understand what law is and are, therefore, without power to evaluate it.

While I would not imply that engineering does not deal with human relations, by and large it seems to me to be concerned with mathematics and the physical sciences and to be primarily concerned with investigating, evaluating, planning, and designing works, structures, buildings, machines, equipment, and processes, which have brought about such a revolution in our mode of living and are the real culprits that have brought about the necessity for so much legislation. But simplification, elimination of useless parts, generalization, ascertaining the common denominator are second nature to the engineering profession, and it is qualities like these that are needed so sorely today as we face the entanglement of conflicting statutes and such a multiplication of "dos" and "dont's" that the ordinary business man and engineer often stand aghast.

Could the two great stable forces of engineering and the law make a greater contribution to public peace and order than by not being too puffed up with professionalism and dealing with the problems as plain citizens, equal members of society by organization, co-ordination, and conscious training? We know that today engineers assist lawyers materially in the preparation and trial of cases where engineering questions are involved. They also frequently are requested to assist municipal engineers in the preparation of ordinances and codes. They also sit on committees charged with the preparation of codes sponsored by different national bodies, and these codes are adopted by municipalities throughout the United States. Why more of them do not seek election to the state and federal legislatures, where they could perform such a wonderful service, perhaps the engineers themselves know better than I.

We must recognize that in our own lifetime the engineers, in effect, have built a new material world. This probably is due to the rapid development of the production and use of electricity, but it applies to all the labors and avocations of man. Men produce more in a given time, travel faster, get world news more quickly, and, in their leisure, have more time for consuming the products of their labor. Still production and consumption are far from synchronized.

The engineer really never is satisfied with the industrial world or any of its devices. He is constantly seeking means to do a given job better and for less cost; higher efficiency and lower operating expense; greater output and smaller unit cost. The engineer is always looking ahead. He never is satisfied unless his enterprise is contributing each year new inventions and improvements on past inventions designed to bring greater benefits to mankind.

The lawyer, however, is generally called in after something has been done that presents a problem dealing with the past—either in the immediate or distant past—and in his consideration of the laws affecting these problems and in counsel to others, he, in effect, must take into consideration the changes in the lives of the people brought about by engineers in industrial development. Certainly the lawyer like any other enlightened citizen does not want to see less made or to give encouragement to those who would advocate curbs on enterprise or production. If the objective of the engineer is correct in working to provide more things for more people at less cost, the lawyer and the engineer, working together, undoubtedly can contribute more than they have in the past through wider appreciation of the economic and social problems involved.

When new developments conceived by the brains of engineers come into being and become a part of our industrial development, the engineer has a right to feel justly proud of his contribution to society. Possibly, by the success of his development, he is spurred to make others; but somewhere along the line someone must design a plan for adapting this new development in our economic life so that it will accomplish the benefactions that spurred its development.

Is it not in this field of engineering, government, and law, dealing realistically with things as they are and not as we would like them to be, that the lawyer and the engineer, each with that broader conception of his separate field of endeavor and his characteristics, can make an added contribution to the welfare of all the people?

Fibrous Glass for Electrical Insulation

By R. E. FERRIS G. L. MOSES

Development of fibrous glass yarn has provided a new insulating material that will withstand high operating temperatures for use in electrical machines

GLASS long has been recognized as excellent electrical insulation, but until recently its use was limited by the form in which it was available to the electrical industry. As a hard, brittle, vitreous material it had definite and rather narrow limitations. With the development of fibrous glass yarns a vast new field has been opened to its use electrically. Its great flexibility, high tensile strength, and resistance to deterioration at high temperatures make it a universally applicable insulation material.

The art of spinning glass into threads of such a size to be used in textiles is not new. However, it was only recently that processes and machinery were developed for producing these minute glass fibers cheaply in great quantities of uniform size and quality. The fibers produced vary from 0.0002 to 0.0003 inch in diameter and are made by two basically different methods.

The "staple fiber" process was first developed and consists of a flow of molten glass through small holes in a platinum bushing in combination with steam pressure. The fibers fly out in short lengths (usually 4 to 12 inches long); these are picked up on a revolving drum and then are spun into yarn and woven into cloth by processes similar to those used by the cotton industry.

Written especially for ELECTRICAL ENGINEERING.

R. E. FERRIS and G. L. MOSES are insulation engineers in the transportation and generator engineering department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

The "continuous filament" process was developed subsequently and consists essentially of drawing the molten glass through fine holes in a platinum bushing. The filaments are wound on rapidly revolving spindles which draw out the molten glass, thereby reducing the size of the filament. In this process the speed of drawing the finished filament controls the diameter. Yarn is spun and woven by processes similar to those used in the silk and rayon industry.

Both processes utilize electric heat for melting the glass. The material is fed into the heating unit in the form of glass "marbles" and the quantity carefully is metered to maintain the molten glass at a constant level. A single "marble" three-quarters of an inch in diameter can be spun into an almost invisible filament approximately 70 miles long.

Since ordinary soda glass is slightly soluble in water it was found necessary to develop a new formula. "Alkali-free glass" was the solution, as it is resistant to moisture. In addition, it has better electrical characteristics, the insulation resistivity being much higher, and it varies less with temperature changes.

Glass fabrics are 100 per cent inorganic and do not deteriorate in mechanical or electrical characteristics at temperatures far above operating temperatures permissible under AIEE rules for class *B* insulation (inorganic materials such as mica and asbestos in built-up form combined with binding substances). Glass tape wrapped around tubes takes a permanent set at 732 degrees centigrade. The "strain point" is 807 degrees and the softening point is 835 degrees centigrade. The industry has far to go before approaching such operating temperatures in electrical machinery.

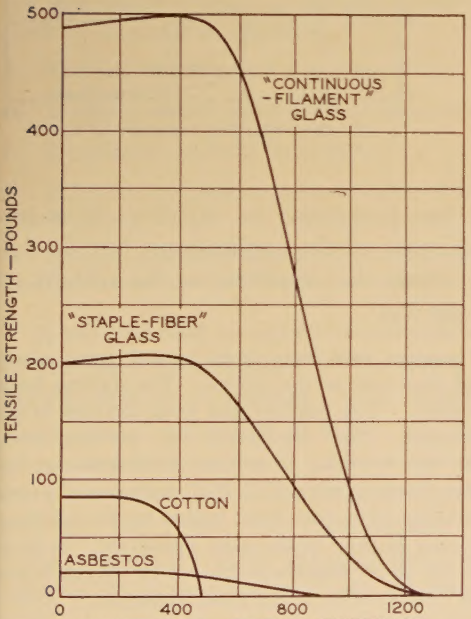

Figure 1. Effect of heat on tensile strength of fibrous electrical insulating materials

Measurements made on tapes 0.01 inch thick by 1 inch wide

The tensile strength characteristic curves of glass tapes (both staple and continuous) are shown in comparison with asbestos and cotton in figure 1. It is significant that both types of glass improve in strength until a temperature of 400 degrees Fahrenheit (204 centigrade) is reached. At that temperature cotton tape deteriorates rapidly and asbestos begins to deteriorate. Staple tape is stronger at 800 degrees Fahrenheit (426 centigrade) than cotton at 25 degrees centigrade, and continuous tape is equally as strong at 1,000 degrees Fahrenheit (538 centigrade).

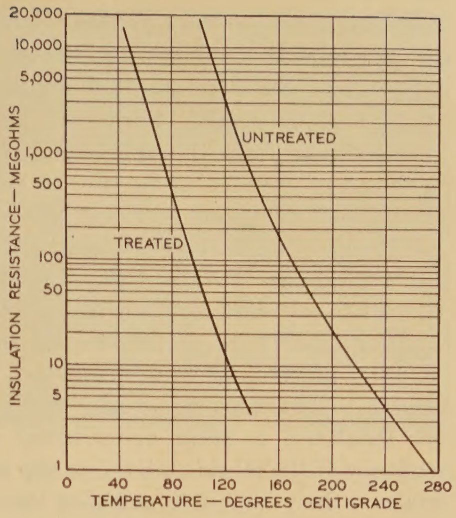

Figure 2. Effect of temperature on insulation resistance of glass tape

Measurements made on test coils having 6 layers of tape 0.01 inch thick built up to a total thickness of 0.06 inch and contact area of 82 square inches

As a dielectric, dry untreated glass tape is comparable with asbestos as both are porous woven materials. Their dielectric breakdown is approximately the same as that of air. When treated, both partake of the characteristics of the impregnating varnish. Glass has the advantage of being nonhygroscopic and has a higher dielectric breakdown than asbestos after exposure to humid atmosphere. Tests indicate that glass (whether treated or untreated) will withstand $1^1/_2$ to $2^1/_2$ times the voltage that asbestos will when both have been exposed to relatively high humidity.

When dry and untreated, glass has a resistivity many times greater than that of asbestos; when treated, they have approximately the same order of resistivity. Figure 2 shows the relative values of insulation resistance for glass insulation on test coils both untreated and vacuum impregnated in solventless varnish and the effect of temperature. When exposed to humidity, glass maintains its insulation resistance to a much higher level. Figure 3 illustrates this on similar test coils insulated with glass and asbestos when both are impregnated in solventless varnish. The insulation resistance of the asbestos-insulated coil fell to 0.5 megohm and failed in 13 days. At 13 days the glass-insulated coil had a resistance of nearly 2 megohms and the curve rapidly was flattening out. The glass-insulated coil did not fail. Figure 4 shows the effect of exposure to various humidity conditions on insulation resistance of glass and asbestos tape.

The insulation of wire is one of the most important applications of glass fibers. The excellent mechanical strength and its resistance to cutting under pressure (where no sharp corners are present) make it well suited to stand abuse in winding and in service. Its ability to withstand excessive temperatures puts it in a preferred position for use as wire insulation in coils that must operate at elevated temperatures or those that may be subjected to occasional severe overloads. Most glass-covered wire is given an enamel treatment to ensure holding the fibers in place. It is possible to apply glass fibers to wire in any thickness from the equivalent of silk on up. The thickness of wire covering can be selected to suit the particular winding and service conditions.

Like all other materials, glass textiles have their definite limitations. In the present state of the art it is difficult to say which of these limitations are inherent and which soon will be eliminated by further progress in methods of producing or using the basic fibers. The principal limitations recognized at the present time are low resistance to shear under sharp cutting edges and tendency of the fabric material to slip because of the silky finish on the yarn. By modifying the technique of handling in the shop, the effect of both these can be minimized. When applying glass fabrics the material should not be snubbed in tension. New weaves are being developed to produce denser cloth with the same thicknesses, which also will counteract the tendency to slip. A practical method used by the authors to counteract this slippage is to vacuum impregnate the rolls of tape in solventless varnish and only partially cure. This is very satisfactory and improves the coil finish. By avoiding sharp edges in applying glass tape, difficulty from the tendency of this material to cut easily will be minimized. Experience indicates that so long as a definitely sharp edge is not present its mechanical strength is high.

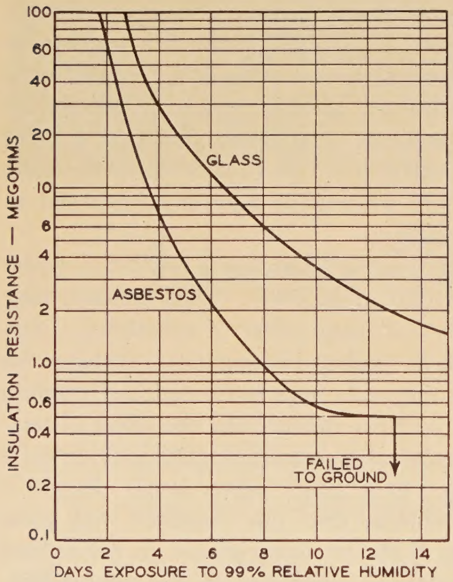

Figure 3. Effect of exposure to relative humidity of 99 per cent on glass- and asbestos-insulated coils impregnated with solventless varnish

Glass insulating materials are available in the following forms:

1. *Tape.* This is available in any standard thickness or width. The present limit on minimum thickness is 0.003 inch for continuous-filament tape, and 0.010 inch for staple-fiber tape.

2. *Braided Sleeving.* This is made from continuous-filament yarns in many standard inside diameters.

3. *Glass-Insulated Wire.* All sizes of round wire are being covered successfully with glass yarn, and many sizes of square and rectangular wire have been covered. Various thicknesses of wall are being used, depending upon the application, to produce an insulated wire size corresponding to standard asbestos-covered, cotton-covered, enamel and paper-covered, and silk-covered sizes.

4. *Woven Cloth.* This is available at present in thicknesses of 0.002 inch and upward.

5. *Combination "Glasweve" and Mica.* Combination slot cells of glass cloth (or mat) and mica splittings are being developed which may result in a higher class *B* insulation for this application.

Textile glass insulation has been used in almost every conceivable application within the few months in which this development has progressed so rapidly. It is impracticable to enumerate all the applications, but the following have come within the experience of the authors on transportation apparatus:

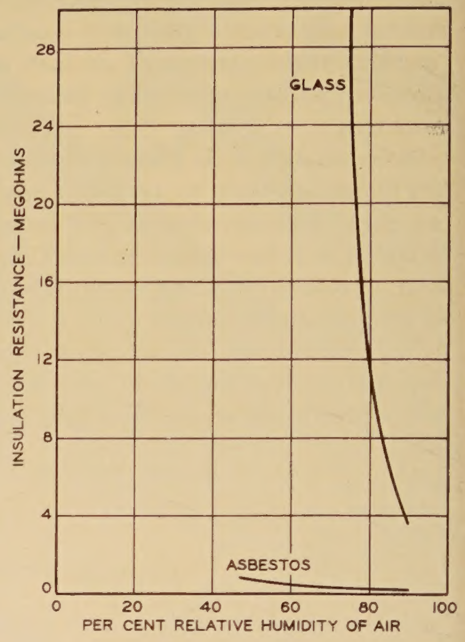

Figure 4. Effect of humidity on insulation resistance of asbestos and glass tapes at 100 degrees Fahrenheit (38 centigrade)

Measurements taken on 0.025- by 1-inch tapes after temperature and humidity had been held constant for 72 hours

1. Many styles of magnet coils have been wound using glass-yarn-covered wire and glass tape on the surface. The starting leads also were taped with glass. This resulted in a great increase in life at very high temperatures. Heat dissipation also was improved. The resistance of the wire covering to cutting under pressure resulting from expansive forces produced at high temperatures was astounding. In laboratory tests, coils were heated to the red heat of copper without serious damage to the glass insulation. Several coils were operated at 500 to 550 degrees centigrade for several hours without any apparent deterioration of the glass insulation.

2. Field coils taped with glass were found to have increased strength of outer insulation and to be more resistant to deterioration at extreme temperatures. Improvements in treatment and appearance of finish were also obtained.

3. Armature conductors were insulated by taping the conductor and by spinning on glass yarn (in the same manner as cotton and silk are applied). This was found to increase the relative life and reduce the probability of short circuits.

4. Armature coils were made using glass binding tape and finishing tape. These withstand higher temperatures without deterioration, and considerable space can be saved over asbestos-taped coils.

5. Armature-coil leads have been sleeved with glass sleeving, or taped with glass tape. This saved considerable space at a crowded spot, and reduced damage from pounding while the armature was being wound.

A relatively large number of commercial applications of glass insulation have been made on railway and trolley-coach equipment which is in everyday service. Several modern high-speed railway-motor armatures and fields have been taped with glass, and a few traction-motor armatures have been wound with glass-insulated wire. On older railway motors, armature coils are being made with glass tape on the outside and on the leads. Many renewal armature coils have been made for high-speed railway motors with glass sleeving on the leads. Traction motors for a prominent a-c main-line electrification had the stator coil ends taped with glass. Many railway control magnet coils have been insulated with glass tape and all have been in operation for several months without trouble. Many magnet coils have been made with glass-insulated wire. Much new transportation apparatus is being built using glass insulation because of the advantages obtained by better space factor and high-temperature operation inherent in glass insulation.

The following is a summary of the advantageous characteristics inherent in textile glass insulation:

1. It is capable of operation under high-temperature conditions, being noninflammable.
2. It has great tensile strength which is maintained to relatively high temperatures.
3. The insulation resistance and dielectric-breakdown strength are both relatively high and are affected less by moisture than are those of conventional materials.
4. The material is nonhygroscopic.
5. It resists attacks by acids, oils, corrosive vapors, and vermin.
6. Its thermal conductivity is high.
7. It is more resistant to a combination of abrasion and vibration than asbestos.
8. Impact, except by a knife edge, can be withstood much better than by corresponding asbestos and cotton tapes.

It may be well to enlarge somewhat on the possibilities of increased temperatures by the use of glass insulation on transportation apparatus. The AIEE rules have defined class *B* insulation in such a way as to permit the use of an indefinite amount of class *A* insulation for structural purposes. For temperatures within the range specified by the rules, this combination material has been very satisfactory, since the maximum temperature for this class of insulating material was established with this limitation in mind when such combinations of organic and inorganic materials were all that was available. However, at temperatures considerably higher than those specified by the rules, the class *A* content of the insulation deteriorates to such an extent that difficulty if not actual failures sometimes will be experienced due to shrinkage of the insulation.

Glass insulation used as a binder and mechanical support in combination with mica offers the possibilities of an insulation that is practically 100 per cent class *B* (except for the treating materials) and thereby places the limitation of temperature on the treating material. This may not be a limit at all on some types of transportation apparatus where high continuous temperatures are encountered, thereby eliminating the possibility of moisture, or in intermittent service where there is little likelihood of moisture absorption. Such a material need not have the same temperature limitations as earlier forms of class *B* insulation, as its aging characteristics under high temperatures will be quite different. It is particularly desirable on transportation apparatus to have insulation that is capable of withstanding temperatures above the nominal upper limits, even though the apparatus may be rated at the conventional temperatures.

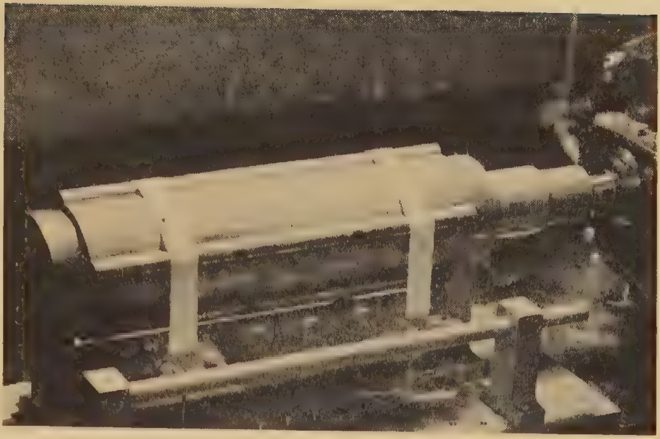

Figure 5. Abrasive life test of glass tape in comparison with other insulating materials

Higher temperatures are, of course, only a means to an end, this end being one of three important characteristics or a combination of all three: first, reduction in size of a machine for a given rating; second, reduction in weight; and third, under certain conditions, a reduction in cost per unit rating. All three are of particular significance in the field of transportation. It is outside the scope of this article to discuss the design of machines operated at higher temperatures, it is not sufficient simply to attempt to increase the rating of a given machine by increasing the volt-ampere input or output. The designer, in order to take full advantage of higher temperatures, must balance his design as regards copper, iron, and stray-load losses. Efficiency must be given consideration in d-c machines, and efficiency and power factor in a-c machines.

Such considerations as expansion and contraction are involved in the use of higher temperatures, but the authors believe that at present the "bottle neck" of the problem is the development of treating material that will withstand higher temperatures. This is in the hands of the chemists whose ability to meet such problems has been demonstrated many times. When this limitation is removed, the possibility of designing even smaller and lighter railway and aviation apparatus with a given rating will be increased yet further.

Much important development work has been done to bring the art of producing glass textile insulation and applying it to its present state. However, a great deal lies ahead in devising means of using its characteristics to best advantage, thereby still further advancing the industry.

The Importance of Research and Development in Maintaining Technical Progress

By M. W. SMITH
MEMBER AIEE

Research and development work usually are regarded as highly technical subjects and generally are so treated, but it is recognized that management has a very definite interest in their influence on technical progress, particularly in the industrial fields. This article is presented with this point in mind, and various suggestions and illustrations are offered as to how this kind of activity may be stimulated and more effectively controlled.

RESEARCH and allied developments are among the greatest factors contributing to the advancement of our standard of living. Through inventions resulting from its application we have traveled farther along the road of technical progress to a safer and more enjoyable life in the past hundred years than in all the preceding time. The last 25 years have surpassed all others and we can expect technical development to progress at an even faster rate in the future.

The scope of research is almost unlimited. It is effectively applied in almost every branch of the basic sciences. It influences the progress and trends of our industries, commerce, agriculture, public health and safety, employment, and even our national defense. While these various branches of research are broadly related and would be very interesting to discuss, it is considered desirable to limit this discussion to the field of industrial research with which the author is best acquainted, so as to indicate better in more specific terms some of the problems and responsibilities of management in the planning and administration of these functions.

Industrial Research and Development

There was a time, not so many years ago, when industry looked to the laboratories of the universities and endowed foundations for its research work, particularly in the fields of basic sciences. While it still recognizes the value of research done by these institutions and attempts to follow it closely through co-operation with them, industry is gradually assuming this responsibility even on fundamental work because results usually can be obtained more promptly by a more concentrated and continuous effort and by limiting the choice of fields of endeavor to those of greatest interest to the particular industry concerned. Although industry may concentrate its research in fields of its immediate interests, progressive companies also follow the work done in allied fields and in basic sciences even to the extent of maintaining fellowships in universities and other independent research organizations. They also maintain close contacts with foreign developments, and history reveals many instances where discoveries were made in one country and subsequently developed and commercialized in another.

Research is one of the most effective and certain means of protecting capital invested in industry from the decay of obsolescence. Reference was recently made in one of the financial papers to an investigation made by the investment divisions of several large insurance companies, to determine from an actuarial standpoint the mortality rate of certain kinds of businesses. One point on which they all agreed and placed considerable emphasis was that the companies which died invariably did little or no research. These companies just gradually "went to seed" with old products which were made obsolete by competitors who developed new methods, processes, and machinery to build products with more desirable performance and characteristics. A progressive company must not only protect itself against the creation of obsolescence from a competitive standpoint but industry in general must strive toward the creation of obsolescence as one of the most effective means of stimulating new business and prosperity. If new business had to depend entirely on the replacement of equipment and commodities which had been worn out or consumed, our progress would indeed be slow and our standard of living and employment would be stagnant. Only through the creation of obsolescence by the introduction of new and improved products can business expect to grow.

Unless we stop and reflect, we are likely to get the impression that our present industries and products have always been in existence, when as a matter of fact, probably one-fourth of our present production is of products entirely unknown 50 years ago, and even those that were known at that time have been modified and improved to such an extent that they can hardly be recognized as the same.

There was a time when business enterprises were quite firmly established and maintained for generations, but the last few decades have seen whole industries wiped out by the forward march of progress. Business men have not fully recognized this danger and adjusted themselves to it. There is still an instinct in the old to fight the new, but nothing except ruin can result from a strict

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Full text of a paper prepared for discussion at the Seventh International Management Congress, Washington, D. C., September 19–23, 1938.

M. W. SMITH is manager of engineering, Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa. A graduate of Texas Agricultural and Mechanical College, from which he received the degree of bachelor of science in electrical engineering in 1915, Mr. Smith has been associated with the Westinghouse company since 1916, when he entered the student apprentice course. In 1918 he entered the power engineering department, and in 1926 was made section engineer in charge of the a-c generator section. He was made division engineer in charge of the design of all large rotating a-c machines in 1930, and appointed to his present position in 1936.

adherence to such a viewpoint or policy where the new is something inevitable because of its economic advantage. A business man is not justified in abandoning an old, established business at the first sight of a substitute product, but neither is he justified in assuming that because it is a substitute for his product it is necessarily an enemy of his. By absorbing it or modifying his product through development work, he may find the opportunity to make his business more profitable than ever.

Aviation may alter seriously the railroad passenger business, but the railroads that have invested in aviation lines will win no matter which way the tide turns. Busses and trucking might put some railroad lines out of business but the railroads that own large bus lines and big trucking routes will carry the traffic in any event. That is the difference between just being in the railroad business and being in the transportation business.

Shortly before the advent of radiobroadcasting, there were probably at least 50 companies in the United States manufacturing phonographs. For a quarter of a century, many of them had done little or no research or development work. Almost overnight, a new form of audio entertainment appeared in the home. It immediately became apparent that the radio music and speech quality was vastly superior to that of the phonograph. Greatly decreased sales resulted in serious financial difficulty in spite of frantic advertising. However, a few of the most progressive companies promptly got in contact with radio experts, and after intensive research, incorporated in their apparatus electronic amplifiers, scientifically designed loud speakers, and electric recording with an astonishing improvement in quality. These companies soon began to prosper once more, while the others who ignored research and development promptly disappeared.

These illustrations emphasize the important part research and development play in the growth of industrial organization, but at the same time it must be recognized that even this activity can be carried to an extreme. Companies can also fail because of too much engineering and development expense if it is not effectively and efficiently controlled.

Types of Research

Depending upon its purpose, research and development in industry can be considered from various viewpoints, but for the purpose of analysis and study of functions and operations, it may logically be considered from the following three viewpoints:

1. Basic, or fundamental, research which involves studies and investigations at the frontiers of the basic sciences of physics, chemistry, etc., to determine the properties, characteristics, and behavior of matter quite without regard to any immediate or specific commercial uses or application.

2. Specific, or applied, research which is conducted to obtain definite information, solve a particular problem, improve an old product, or develop a new product or line of equipment.

3. Commercial development, which has for its purpose extensions to existing lines of products and improvements in their characteristics and performance. This type of development is not directed toward the discovery or perfection of new kinds of products, but toward improvements and cost reductions in existing ones so as to enhance their competitive standing or value.

Fundamental Research

The nature of fundamental research requires that it be undertaken on a comparatively long-range basis and the fact that important results or achievements may not be realized for several years should be recognized. Here the problem of management is largely one of the proper selection of personnel and general fields of investigations. The success of this kind of work is largely dependent upon individual effort and management can provide only limited detail supervision. The personnel must be selected with this point in mind. In addition to good technical ability and qualifications, men for this work should have an abundance of initiative, enthusiasm, courage, and imagination. The recognition of the importance of the selection and development of men for research work has been demonstrated by the establishment of special training courses and opportunities to do advanced work in industry.

For instance, the company with which the author is associated recently adopted a plan for the establishment of ten positions in its research laboratories, to be known as "research fellowships." These fellowships will be open to young scientific workers in physics, chemical physics, physical metallurgy, etc., enabling them to carry on studies of pure scientific value in these fields. Appointments will be made for a one-year period, with the possibility of renewal for a second year. Applicants are required to have training equivalent to a doctor's degree and have already demonstrated ability of a high order in scientific research. In this way it is hoped that a steady stream of the best young scientists will pass through the laboratories in years to come. While there are no definite committments, it is expected that some of these men will want to remain on the regular staff of the laboratories. Others will return to academic work in leading universities and other institutions after having acquired an insight into the scientific problems of the electrical industry. While the research fellows will be given considerable freedom as to the particular research problem on which they will work, it is expected that in all cases, the broad field of work will correspond to one of the existing activities of the laboratories. It is planned to keep the working program as flexible as possible in order to adapt it to current progress in physics and chemistry. Experience indicates that important advances in industry may be expected from fundamental knowledge gained through such a program and the operation of this projected fellowship plan should also serve to keep the laboratories in closer contact with other scientific institutions with which these men may later become associated.

Specific or Applied Research

Although specific, or applied, research cannot be sharply distinguished in all cases from fundamental, or pioneering, research, its purpose is different in that it is usually conducted with a definite objective in mind and with the idea of early application. It represents the major activity of most industrial research laboratories because it is usually directed toward improvements in established lines of equipment. For instance, because of troubles experienced on a new product or because of the desire to extend the application of an existing product into new fields of application beyond previous limits of knowledge and experience, certain information and data may be necessary. This may require some fundamental research but it is largely a question of finding the answer to a problem which already exists and is not of a pioneering nature.

Because of its nature, applied research is often subject to the pressure of production from other divisions of the company, which have a commercial interest in the project. This condition, together with the fact that the management has an appreciation of the nature and scope of the problem, presents the opportunity, and even necessity, for much more supervision and direction of the work than can be expected on fundamental subjects. This kind of work must be followed closely and actively by the management to see that it progresses with reasonable speed and that specific projects are not drawn out beyond profitable limits. It is just as important to know when to stop an unpromising project as it is to start an attractive one. Moreover, the pressure for immediate results on specific subjects should not be allowed to crowd out fundamental work which is likely to be neglected because of budget limitations or because immediate requirements or prospects do not appear urgent.

Effective and efficient operation requires careful consideration of the organization and personnel and the classification of the types and scope of the work. In a large laboratory it is usually advisable to group the organization into several divisions with personnel and equipment best suited for work in a particular field or branch of science. This is particularly desirable if there are a large variety of subjects to be treated which can be grouped into general classifications. On the other hand, care must be used to avoid building barriers between divisions which will unduly limit the exchange of knowledge and experience between them. Quite often the knowledge obtained or the method of analysis or approach used in the solution of one problem may be quite helpful in attacking another. It is therefore desirable to set up effective systems and regulations for exchanging and disseminating information and results of investigations throughout the organization by means of adequate records, reports, seminars, conferences, etc. Adequate library facilities are also essential in this plan. All current literature should be carefully scanned and items of interest on various subjects should be summarized and referred to those particularly interested in or engaged in work on the subject. The practice of becoming thoroughly acquainted with the status of the art through surveys of existing literature before work on any new project is actively started should be encouraged.

Incubation of New Products

Out of basic fundamental research or even as a byproduct of some specific research on another subject may come a new idea or product which has the possibility of commercial development and exploitation. Here management has a very definite problem and responsibility which often is neglected. A review of products which have come out of research indicates that few of them seemed to be important at the time they were first conceived. It is beyond the power of human conception and vision to recognize the future value and possibilities of many such developments and it is only after they have had an opportunity to spread their effect over a period of time that they are fully appreciated. Nevertheless, management must continually be alive to its obligations and take steps to encourage the practical development of new ideas and eliminate barriers which too often exist in their path.

An illustration of the obscure nature of discoveries is found in the phenomena connected with the discharge of electricity through gases. The faint glow discharges which it is possible to get in tubes with gas at low pressures first attracted only the scientists and physicists in the laboratory nearly 50 years ago. This toy of the scientist, however, led to two outstanding discoveries. The first was the discovery of the electron by Thompson, which historians will probably regard as the most important technical event to date. The second was the discovery of the X-ray by Roentgen, which has done much to alleviate human suffering and to prolong life, primarily because of its use for diagnostic purposes but also through direct treatment of disease.

The first attempts to use these glow discharges commercially were in the field of lighting, through the work of Moore and Hewitt in developing the mercury-vapor lamp. Today it is not the high efficiency which makes this type of light attractive, but the brilliant and unusual colors which are obtained in neon signs. Another development coming from these gas discharges is in the form of rectifiers and inverters for the electrical power field. One of the most recent applications of the gas-discharge principle, unforeseen in the early days, is the development of a special tube by Rentschler and James, which has very high lethal, or germicidal, powers.

Sometimes a specific development is not complete within itself, and other developments requiring research in allied fields must be completed and combined with it before a commercial success can be made of the idea. A better realization of this condition and responsibility by those in charge of the over-all activity should work toward the elimination of unnecessary delays in the progress of commercial development.

In 1880, a man by the name of Fritts, a pioneer inventor, filed a patent application on talking motion pictures. A review of this case will show that it contained practically all of the fundamental features which exist in the art at the present time. Yet the commercial application of talking pictures was delayed a generation because the elements called for were not promptly developed. For example, his photosensitive device would not respond to the frequencies of speech and music.

It is recognized that the progress of such basically new ideas necessarily must be slow because of human limitations and lack of appreciation of future commercial possibilities. However, a better realization of this lack of appreciation and the acceptance of the responsibility on the part of management to see that steps are taken to develop component parts and principles instead of allowing new ideas and products to flounder around in the laboratories for lack of attention, should go a long way toward accelerating the progress of new developments.

Pilot Plants

Sometimes the difficulties encountered in promoting a new product of the laboratories are much more real and specific than the lack of vision to perceive their potential possibilities. Large industrial companies usually are organized into divisions which are responsible for the design, manufacture, and sale of established lines of products. They are likely to be reluctant to take over a new product until its market and profit possibilities have been determined. This condition often results in a long delay between the research development stage and the commercial application of the product.

To eliminate this unsatisfactory condition usually requires some intermediate stage of development. It is not practical to do commercial development work involving the study of manufacturing processes and cost reduction methods in a research laboratory. On the other hand, established operating divisions of a company, which are charged with the responsibility of making a satisfactory profit, cannot be expected to take over a new product until its commercial possibilities have been investigated. An intermediate organization is therefore desirable to carry the new product through the necessary incubation stage to determine its commercial value. Many of the chemical industries have solved this problem satisfactorily by the establishment of "pilot plants," where new processes are developed on a commercial scale. This general idea is now being successfully applied in other types of industries and can be expected to accelerate technical progress and developments in the future.

Very careful consideration and good business judgment must be exercised in the selection of new projects to be reasonably certain that they have sufficient merit and commercial possibilities even to justify carrying through an incubation stage. Here management has a difficult and somewhat paradoxical problem of not being overpersuaded by the enthusiasm of the inventor and at the same time maintaining the enthusiasm of the research personnel when their projects, in which they are personally interested, are turned down for lack of economic or commercial value. While the maintenance of an optimistic point of view is desirable, business cannot ignore economic considerations. The morale of the research group can usually be maintained in such cases by a frank discussion of the reasons for the decision. It should be realized that in spite of careful selection and accelerated progress, unprofitable operation on new products for prolonged periods is the rule which in turn increases the risk industry must continually assume and is a fact which is not generally appreciated by the public.

Commercial Development

In the final analysis, the climax to all industrial research and development work is the purchase and use of a new product by the ultimate consumer. It is therefore essential to study the consumer's needs and desires as a guide in the development of new products and to follow his reactions to newly developed products to determine their acceptance. The increasing importance of this viewpoint has been recognized and market analyses and studies of the trends of consumers' needs and desires are being reflected back down the line in such a way that they have a large influence on commercial development.

In large industrial organizations, commercial development work is usually conducted outside the research group and by the operating divisions who are responsible for the design, manufacture, and sale of various lines of established products. This work is largely directed toward the elimination of minor troubles and the application of improvements in performance reliability, appearance, etc., so as to increase the public appeal and acceptance of a product. It involves the study of material processes and standardization, manufacturing methods and procedures, tool equipment and production methods, and cost reductions of all kinds. Although this kind of work has a very definite and specific objective, it often brings out limitations and lack of knowledge and information which lead to research work of the types described above.

Influence of Patents

A discussion of the subject of technical progress would hardly be complete without emphasizing the important influence of the patent system, particularly at this time when there seems to be so much agitation in some circles to place limitations on private research and patent rights. It has been stated that "no fewer than 15 bills to prohibit the patenting of labor-saving machinery or improvements thereof have been introduced during the present Congress." A great deal of our technical progress in America can be credited to our patent system, and any action to limit its protection would indeed be regrettable. It costs money to develop and exploit inventions. The protection afforded by patent claims provides incentive to develop new things and under such conditions they may be exploited for a long enough time to become established. Without such protection, capital could not afford to venture into new fields, and industrial research would become very secretive, and because of the resulting lack of co-operation, our great advances in living standards and human comfort would be seriously handicapped. Let us be determined to support and encourage individual and private initiative rather than curb it, so long as it is based on sound economic foundations. Scientific advances based on economic improvements are inevitable. Economic laws and human nature cannot be effectively legislated against.

Attitude of Management Important

In this discussion, development activities and functions have been broken down to some extent in an effort to clarify and illustrate methods of control and supervision, but it is recognized that close co-operation and co-ordination of all phases of the work are essential to successful operation. Francis Bacon recognized the importance of organized research as far back as 1620, when he said:

> If many useful discoveries have been made by accident or upon occasion when men were not seeking for them but were busy about other things, no one can doubt but that when they apply themselves to seek and make this their business, and that, too, by method and in order and not by desultory impulses, they will discover far more.

It is almost axiomatic that technical progress is dependent entirely on progress or accomplishments in research and development work in the various branches of science, and unlimited illustrations could be supplied to substantiate this claim. It therefore appears that the greatest responsibility—or probably we should say opportunity—of management in maintaining technical progress is to accelerate research and development work through better administration and control of organizations engaged in this kind of work. In addition to a more rigid application of the usual principles of efficiency and economy of operation, a sympathetic and encouraging attitude on the part of the top management of a company is considered essential. This promotes co-operation and teamwork among the personnel of research groups and is conducive to good performance, which, after all, is a large factor in the determination of the rate of our future progress.

No invention or development is an unmixed good even though it may be based on sound economic principles. As inventions enlarge our activities and broaden our lives in one direction, they cause shrinkage and distress in another. It is the gradual but positive net progress over a long period of time which counts and we must not become disturbed and thrown from our long-range course by temporary upsets in our social and economic progress. Any basically new idea is really beyond our comprehension and vision. If we could visualize it, it would be immediately developed. However, we may be sure that engineers and scientists will continue to make new discoveries—new ways to heal and save, new ways to kill and destroy; and out of it all we will have new joys and new sorrows along the road of progress to better standards of living.

Amplitudes of Magnetomotive-Force Harmonics for Fractional Slot Windings

FRACTIONAL slot windings have certain well-known attributes which cause them to be quite generally used in synchronous machine design. However, a winding occasionally will be produced which will develop harmonics in the air-gap magnetomotive force that will lead to excessive losses, vibration, and noise. The purpose of this paper* is to develop general formulas for computing the distribution factor and pitch factor of any magnetomotive-force harmonic set up by three-phase fractional slot windings of normal design, in order that a winding arrangement may be chosen that will minimize ill effects. The formulas are said to be sufficiently simple to permit a complete tabulation of distribution and pitch factors over the normal range of slots per phase per pole now used in fractional slot windings.

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*Abstract of 1938 AIEE summer convention paper number 38-53, by J. F. Calvert (A'27, M'35) which will be published in full in TRANSACTIONS.

Reactance of Square Tubular Bus Bars

SQUARE tubular bus bars are being used to an increasing extent, as they are economical and convenient for joining to insulators and to branch circuits. The reactance of busbar circuits frequently is of importance, in order that the voltage drop under normal conditions and the current under short-circuit conditions may be computed. The purpose of this paper* is to present formulas and curves by which the reactance of square tubular bus bars may be determined.

Curves are given showing the reactance of thin square tubes, assuming uniform distribution of current, and the approximate corrections for rounded corners and thick walls. Illustrative examples show practical use of the method of computation.

The reactive drop in each conductor of a group of parallel conductors may be expressed in terms of single-phase reactances by first expressing them in terms of self- and mutual inductances and then arranging them in pairs. An example for a three-phase bus bar is given.

Selection and Design of the Electrification of the San Francisco-Oakland Bay Bridge Railway

THREE railway companies will operate electric trains over the San Francisco-Oakland Bay Bridge, using a dual-voltage system that supplies 600 volts from a third rail and 1,200 volts from an overhead conductor. Reasons for the selection of this system and the plan of the electrification are given in this paper.†

Mercury arc rectifiers provide direct current for the electrification from three substations, two of which supply both the 600- and 1,200-volt systems while the third supplies the 600-volt system only. The running and guard rails, which are used for the return current, are bonded carefully to prevent leakage of current to the bridge structure. Special problems were met at expansion joints because of the extraordinary length of the bridge, the movement amounting to four feet per joint in some instances.

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* Abstract of 1938 AIEE summer convention paper number 38-79, by H. B. Dwight (A'11, F'26) and T. K. Wang, which will be published in full in TRANSACTIONS.

† Abstract of 1938 AIEE Pacific Coast convention paper number 38-99, by W. P. Monroe (A'19, M'26) which will be published in full in TRANSACTIONS.

Chemistry and High-Voltage Dielectrics

By F. M. CLARK
ASSOCIATE AIEE

Development of high-voltage dielectrics to meet the increasingly exacting demands of modern applications challenges chemical ingenuity and constitutes the broad avenue of chemical approach to the problem of high-voltage engineering

THE PROBLEM of the high-voltage dielectric can be approached from the physical or chemical standpoint, although the traditional approach is along the pathway of physics and engineering. The insulating properties have been considered as largely inherent and fixed. The object has been to determine their variation with changing environment. Such attempts as have been made to "lift the cover" have been carried out chiefly by students of molecular structure interested in a study of the fundamental nature of matter. This method of physical attack has been successful in that it has been able to classify and apply materials commercially on the basis of their "normal" dielectric properties. Since some of the most common commercial insulating materials, such as mineral oil and paper, are good insulators, the physical method of attack perhaps has been the one heretofore best adapted to produce the most rapid progress within established electrical demands. The more stringent requirements of the present time, however, cannot be met even by an unceasing search for standardized products. The properties of dielectrics must be considered as living, not dead—as flexible and controllable. Voltage and heat, ever present factors in the use of modern high-voltage insulation, must be looked upon as reagents of reaction, the course and speed of which is variable in accordance with the recognized laws of chemical change. Dielectric-test results must be considered not as a fixed and immutable goal but as tools to a chemical answer. Dielectric defects revealed by physical tests on existing materials are not to be considered as warning signs indicating the end of the road. The pathway of dielectric progress is not a dead-end street. Dielectric defects must be considered only as detour signals clearly legible when expressed in terms of chemical behavior. The marked progress of industrial chemistry during the past several decades has been made on the recognition that naturally occurring products are not necessarily the ultimate in perfection. Studies of the chemical requirements demanded and the synthesis of improved materials invariably have marked the line of progress. Mineral oil and cellulosic insulations are no exception. Important as these products have been in the history of electrical insulation, materials better adapted for high-voltage insulation are possible. The development of such products challenges chemical ingenuity and constitutes the broad avenue of chemical approach to this phase of engineering progress.

Dielectric Strength

When one considers high-voltage dielectric practice, if one approaches the problem in the traditional manner, one turns at once to the property of dielectric strength. Questions relating to its vagaries at once arise. What is the effect of temperature? How does the strength change with thickness? If one follows such an attack, one determines the response of the dielectric to changes in environment and ultimately develops empirical mathematical relationships clearly describing the material under study, but yielding little or no information concerning how materials can be developed that are better adapted for the use at hand. Such an attack leads to a description of dielectric behavior as is included in the so-called pyroelectric theory of dielectric breakdown. Insulation fails because of heat accumulation. Of course it does, but such a statement is superficial. Where does the heat come from? Why does heat accumulate, assuming proper engineering design? I have asked that question of engineers and physicists and have universally received the same answer—"from changes in the electrical-loss characteristics of the insulation." The step from this explanation to the chemical attack on the problem is obvious and presents what the author has chosen to consider as the first chemical approach to the problem of high-voltage dielectrics. If changes in loss occur, they must be due to some fundamental change in the material itself.

The physical investigator says that changes in electrical losses come from changes in the material resulting from the applied-voltage stress, oxidation, heat, or other factors, all of which are classified by the chemist as "reagents of reaction." There is the opening for the chemist. Dielectric breakdown in service is due to a deteriorating chemical reaction initiated and accelerated by the conditions of service imposed. Breakdown of insulation is fundamentally chemical, not physical. The

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physical manifestation of breakdown only follows the deterioration produced by chemical changes. The passage of the arc is the culmination of the whole previous chemical history of the material.

Physical studies of the dielectric strength are usually tests for accidental contamination. In dielectric liquids, the test is often merely a means of detecting suspended particles and water. In the solid dielectric, it is frequently a test detecting conducting particles. In several instances the author has said that all organic materials are characterized by good dielectric strength when pure. The practical problem is usually that of purification. This offers a second avenue of chemical approach, for the chemist, of all scientists, is best trained for the solution of such problems. His knowledge of chemical stability and chemical behavior is invaluable in the development and application of improved purification processes.

However, all insulating materials, when pure, cannot be said to be characterized by good dielectric strength, without some reservations. Not all materials have equal dielectric strength although all materials may have good dielectric strength when pure. For example, if one tests the dielectric strength of mineral oil as commercially prepared and water free, the normal dielectric strength is about 30 kv under the usual conditions of test. Under the same conditions of practical preparation and test, the dielectric strength of other liquid materials of similar viscosity may be from 30 to 100 per cent higher, depending on the actual conditions of test comparison. The liquid chlorinated hydrocarbons, for example, are characterized by a normal dielectric strength from 30 to 50 per cent higher than that of mineral oil. It may be suggested that this is merely evidence of a greater resistance of the chlorinated hydrocarbons to contamination, but in the gaseous state the chlorinated derivative also possesses a higher dielectric strength than the parent hydrocarbon. Yet even conceding that the increased dielectric strength of the chlorinated hydrocarbon liquid is due to a greater resistance to deteriorating influences, the result is the same. Materials are used under the ever present threat of contamination. That material which possesses the greatest resistance to deterioration of any type is the most practical. The conclusion is inescapable that from the dielectric-strength standpoint, naturally occurring products such as mineral oil are not characterized by the high value associated with synthetic hydrocarbon derivatives. The problem before the chemist is the proper selection and synthesis of these improved dielectric materials. The solution of the problem offers another chemical means of approach, but fundamental and basic research is needed before the goal will be reached.

Dielectric Stability

The property of initial dielectric strength, while fundamental in all lines of dielectric application, is not the only problem offering opportunity for chemical research. In fact, in most dielectric applications it almost might be stated to be the least important. Insulation rarely fails because of a defect in the initial dielectric strength. Careful chemical supervision of stock materials is an adequate protection against such troubles. Insulation in service usually fails because of deteriorating chemical changes arising under the conditions of service. These chemical changes result either in gas evolution, with consequent ionization effects, or merely in increased electrical losses which in turn cause dielectric failure through thermal disintegration of the dielectric—in other words, failure in accordance with the engineering concept of pyroelectric breakdown. The problem is directly manifested as one of dielectric strength. Fundamentally, the problem is one of chemical stability.

Chemical stability, at least in the author's opinion, is the most important property of any material used in engineering design. It is no less important in dielectric engineering than in the manufacture of rubber tires, lubricating oils, dyes, drugs, foods, and many other items, the instability of which has presented problems successfully solved by the chemist in the past. Many times the author has stated that the adaptability of a material for high-voltage-dielectric engineering can be gauged most accurately from a study of its chemical reactivity. Reactive materials are poor dielectrics for high-voltage engineering. This perhaps naturally follows from the molecular structure of the materials themselves. Reactivity and conductivity appear to be closely related to the polarity of the molecule. Marked polarity invariably is accompanied by marked reactivity and high electrical losses. Other factors such as viscosity being equal, marked polarity in molecular structure normally is accompanied by high solvent action and decreased resistance to electrical contamination by materials unavoidably present in electrical usage. The problem of the chemist is the synthesis of molecules capable of retaining their original identity against a variety of reactive reagents among which are heat, oxygen, and voltage stress. Given such characteristics, the other properties in most instances with which the author is acquainted are automatically obtained.

Of all organic chemists, the petroleum chemist perhaps has devoted the greatest amount of time and effort to the satisfactory solution of this problem. He has made marked improvements in his product in the past decade. In cables he has produced an electrically more stable product. In transformers, he has produced a product more free from sludging tendencies. Yet fundamentally he is fighting a losing battle if in the future he pursues the line of attack followed in the past. Refining experience to date has been based on the assumption, probably true, that mineral oil is a compromise product. Refining is a compromise between too little refining with attendant chemical instability of one type, and too much refining with attendant instability of another type. Such a product, once chemical research is aroused to the possibilities offered, cannot continue in use. Either the petroleum chemist must isolate and remove those materials the presence of which in mineral insulating oil constitutes the dangers comprised in the terms "overrefined oil" and "underrefined oil," or give way to the newer synthetic materials of improved stability.

But the problem of stability is only in its fundamentals a simple problem. Of course, the best material for high-voltage-dielectric engineering is that one which will retain its original identity under all conditions of use. It is inert under extreme voltage stress and extreme oxidation conditions. Such a material probably will not be immediately available. Perhaps the electrical industry will not suffer much if it is never available, for both fortunately and unfortunately such a product is not the only solution to the problem—fortunately, since such a product may never be found; unfortunately, since the questions arising from the possibility of using less stable materials without sacrifice are many and complicated. This is because high-voltage dielectrics are rarely, if ever, simple materials. Most dielectric problems involve at least two dielectric materials. In general, these are a mineral oil and the treated paper.

The fact that liquid and solid are used together raises questions of stability that can be answered only by the organic chemist. For example, two types of oil may be cited, each refined in accordance with similar technique but each with a different source of crude oil. Each, when chemically oxidized in a beaker, shows the same degree of electrical and chemical deterioration. Yet when tested in composite paper structure under the same conditions, one oil yields electrical stability and the other electrical instability to a degree that makes its commercial use doubtful and dangerous. Another oil will darken and increase more rapidly in acidic properties under oxidation than a second oil of similar characteristics, yet in turn will show increased electrical stability in the treated paper structure. What is the answer? The answer is obviously that the products of the chemical reactions and the dispersion of these products through the dielectric assembly determine the degree of resulting electrical instability. Yet who knows which products of mineral-oil oxidation are electrically innocuous and which are not? And who knows how to modify the present refining treatment of mineral oil in order to avoid the formation of electrically dangerous oxidation products? Comprehensive research in the chemical field alone can answer this question. The electrical tests are merely tools to a chemical answer.

Contamination Effects

The problem of stability cannot be solved merely by attention to the electrical changes observed in the material isolated from members of the assembly in which it may be a part. The problem is more complicated. Neither can the adaptability of a liquid, for example, be determined solely from its initial dielectric properties as compared with a standard. Our ideas of impregnating liquids of course are colored largely and unfortunately by our experience with mineral oil. Thus, from mineral-oil experience it often has been concluded that a dielectric impregnating liquid for high-voltage use must have a resistivity of at least 10^{14} ohm-centimeter at 100 degrees centigrade, and the higher the better! Yet experience shows that liquids with resistivities as low as 10^{11} or 10^{12} ohm-centimeter may be even better suited for electrical impregnating use. It is the chemistry underlying the actual electrical properties that is important. Each liquid material from the practical standpoint has a normal level of electrical resistance or a-c loss above which it can be maintained only with difficulty and below which only the presence of highly active, conducting contamination can cause it to go. For mineral oil, this normal value may well be 10^{14} ohm-centimeter. In general, the contamination that would lower the resistance of mineral oil to 10^{10} or 10^{11} ohm-centimeter is of the chemical type which would render the oil unsuited for electrical impregnating applications, not because of the lower electrical resistance, but rather because of the chemical character of the contamination per se. Yet a second liquid of normal resistance in the range of 10^{10} to 10^{11}

Some of the apparatus used to make electrical measurements that are valuable tools in the chemical development and control of dielectric materials ohm-centimeter may be better than the first, even in its highest degree of electrical resistivity and loss properties. It is the chemistry and the chemical reactivity of the contamination that is important, not the simple electrical value in itself. Studies in this field having the object of isolating those substances that threaten the stability of liquid-treated insulation offer another fertile field for the research chemist.

The Oxidation Inhibitor

When a chemist finds that a certain type of molecule is objectionable, he invariably attempts to synthesize a product the structure of which eliminates these defects. However, another method of attack is the synthesis of a stabilizing agent. The commercial importance of stabilizing agents, retarders or antioxidants is indisputable. Because of the dielectric demand, however, the problems involved in the use of stabilizing agents in electrical insulations, are somewhat more complicated than in many other applications.

Oxidation is without doubt one of the major chemical problems facing the dielectric engineer. If oxidation could be eliminated completely, many of the problems of dielectrics would be simplified. In some instances it seems that the complete elimination of air in oil-filled apparatus can be guaranteed, yet the oil shows oxidation. What is the source of the oxygen? Can it be obtained from the cellulose molecule under high-voltage stress? Some evidence indicates that it may be so obtained. A cellulose chemist can offer the electrical industry real service by the elimination of this source of oxygen supply, if research shows that it does exist.

But assuming that the danger of oxidation cannot be removed either by the mechanical engineer with his design ingenuity or by the chemist with his synthesis efforts, there remains then only one way out—the use of oxidation inhibitors. While inhibitors have been developed for use in all sorts of things from foods to rubber tires and lubricating oil, the adoption of such products in electrical oils has been slow. The retarder itself must be studied not only from the standpoint of its efficiency in blocking oxidation, but also from the standpoint of its own dielectric stability. Small amounts of material dissolved in mineral oil, for example, can seriously affect the dielectric characteristics of the oil and, more important, of the oil-treated dielectric irrespective of oxidation effects which may be reduced or eliminated. Oxidation inhibitors therefore, even when used in small amounts, cannot be considered satisfactory without careful consideration of the dielectric results produced by the presence of the inhibitor initially and the effect produced by products arising from the chemical changes in the inhibitor under voltage, heat, and oxidation. Progress in this field cannot be aided by the blind adoption of an inhibitor just because the material has given excellent service in the rubber-tire industry. Careful research and dielectric investigation are needed to remove the fear of retarders which many dielectric engineers have at present simply because they have not been able to substantiate in the electrical field many of the recommendations ill-advisedly and thoughtlessly made to them, based on the behavior of the same inhibitor in other applications. The development of a satisfactory inhibitor for use in oxidizable insulating compositions presents to the chemist another important means of approach in his attack on the problems of an improved high-voltage dielectric.

Dielectric Constant

There is one property of insulating materials that is sold as such by the electrical industry. This property is the dielectric constant. It is sold substantially unchanged to the trade in the form of an electrical capacitor. The problems of stability, electrical losses, and electrical breakdown must be solved if efficient electrical service is to be obtained. These problems apply to all types of electrical apparatus containing insulation operating under high voltage. They apply with equal and perhaps greater force to the electrical capacitor which operates at as high, if not higher, voltage stress than any other electrical apparatus. Fundamentally, however, the electrical capacitor sells the dielectric constant. And the dielectric constant is one of the fundamental properties of the chemical molecule that the chemist can change at will. Starting from the parent molecule he can produce changes in dielectric constant simply by group substitution reactions. It is true also that he produces simultaneously a wide range of chemical reactivity and flammability, electrical losses, and stability, but the fact remains that he alone knows how to change the fundamental nature and properties of the molecule at will. He should be anxious to accept the challenge presented by the capacitor—to produce a high-dielectric-constant solid or liquid impregnating material suitable from the standpoint of other properties for use in electrical capacitors.

Not many years ago mineral oil was considered the only material suited to meet these stability requirements demanded by capacitor use. But mineral oil possesses a low dielectric constant. Today mineral oil has been largely replaced in the high-voltage field. The synthetic chemist has produced an improved product, chlorinated diphenyl. This synthetic liquid has many of the ideal properties so urgently demanded. The product is stable, nonoxidizing, noninflammable, of high dielectric strength, and reproducible with the usual greater reliability of a synthetic product in comparison with a natural product such as mineral oil. Physically the size of the capacitor has been reduced at least 50 per cent from the dimensions per kilovolt-ampere formerly associated with the use of mineral oil. Progress is being made, but the problem is not solved. The surface has only been scratched, and this single example of what has been done by the chemist has been cited in the hope that its accomplishment may stimulate increased interest on the part of the chemical profession and result in a closer union of the engineer, the physicist, and the chemist, each of whom has an important role to be played if the present and future problems of dielectric engineering are to be successfully solved.

Lightning to the Empire State Building

By K. B. McEACHRON
FELLOW AIEE

Combined photographic-oscillographic studies of lightning strokes to the 1,250-foot Empire State Building in New York City during the past several seasons, have confirmed some previous ideas pertaining to the nature and mechanism of the lightning discharge and have provided additional information enabling a more complete picture of this phenomenon to be drawn.

IN THE PROBLEM of protecting electrical apparatus from lightning, not only should the magnitude of the current and frequency of occurrence be known, but, of equal importance is a knowledge of possible wave shapes—how fast is the front in terms of amperes per microsecond, how slow can it be, and how long does the current persist? In the case of the multiple stroke, are the succeeding wave shapes like the first one, or how may they differ?

In an effort to throw additional light on these and other questions pertaining to the mechanism of the lightning discharge, a combined photographic and oscillographic study of the lightning strokes to the Empire State Building in New York, N. Y., has been made during the past four summers. Photographs of the strokes were taken with a variety of Boys (moving-lens or moving-film) cameras, while the cathode-ray and crater-lamp oscillographs furnished information pertaining to wave shape.

No effort will be made to make a complete summary of the results of this work, but some of the most important findings are as follows:

1. Oscillograms, or moving-film Boys-camera photographs, or both, have been taken of 55 strokes to the Empire State Building.

2. Direct-current arcs, with or without superimposed current peaks, extending between the cloud and the building continuing as long as 0.4 second, have been measured. These have been called continuing strokes.

3. Upward leaders from the building that developed into continuing strokes have been photographed, and data as to velocity of propagation secured. (Upward leader velocities range between 0.17 and 2.09 feet per microsecond with an average of 0.84 feet per microsecond.)

4. Currents measured during build-up of upward stepped leaders range from 50 to 650 amperes.

5. Branching was found to be in the direction of propagation of initial leader strokes.

6. At least 50 per cent of the strokes had a charge of 35 coulombs or more with a maximum of 164 coulombs. These values are several times as large as heretofore believed probable.

7. All strokes to the building began with the cloud negative. Three strokes changed to positive at or near the end of the stroke. About three per cent of the total charge measured was associated with the positive portion of the strokes.

8. Downward stepped leaders to the building were observed in one stroke only which had a velocity of 14 feet per microsecond. A stroke to a building 200 feet in height had a downward-stepped-leader velocity of 5 feet per microsecond.

9. Leaders on all discharges after the first always were downward whenever found, whether the initial leader was upward or downward. Such downward leaders had velocities ranging from 1.9 to 128 feet per microsecond with an average of 39 feet per microsecond.

10. Return-stroke velocities following initial stepped downward leaders were 340 and 150 feet per microsecond in the two cases recorded, while the returnstroke velocities following continuous leaders ranged from 98 to 280 feet per microsecond with an average of 197 feet per microsecond.

11. Every stroke but two of which the author has record, either struck the highest point on the building or outside a cone the base radius of which at the ground level of the building was equal to the building height.

Empire State Building

The Empire State Building in New York City is a steel-frame building surmounted by a metal tower, the top of which is 1,250 feet above the street. Extending above the top is an antenna system of the National Broadcasting Company used for television experiments. The antenna system in use during most of the investigation is shown in figure 1, but some of the earlier work was done with an antenna system of a somewhat different design. Approximately in the center is an antenna that extends above the triangular system and terminates at a point 38 feet above the top of the building. At a point 11.6 feet downward, the $1^1/_2$-inch duraluminum rod enters a 5-inch (inside diameter) brass pipe, being spaced from the pipe by suitable insulator.

During the taking of all the oscillograms discussed in this article, the inner conductor and outer pipe terminated at a point about 11.3 feet below the roof in a noninductive shunt having a resistance of 0.03 ohm, which is a part of the shunt used with the cathode-ray and crater-lamp oscillographs.

Prepared especially for ELECTRICAL ENGINEERING, based upon material presented in addresses to various AIEE Sections; a more detailed treatise on these studies is scheduled for publication in an early issue of the *Journal* of the Franklin Institute.

K. B. MCEACHRON is director of high-voltage research at the Pittsfield, Mass., works of the General Electric Company. He is currently an AIEE director and chairman of the Institute's committee on protective devices. A biographical sketch was published in the October 1938 issue, page 434.

The author and his associates wish to express appreciation to the National Broadcasting Company and the NBC engineers, particularly R. M. Morris and T. J. Buzalski, for making it possible to take measurements of lightning currents through the antenna, and allotting space in the top of the building for the oscillographs. Fletcher and Ellis kindly made available space in their offices in the building at 500 Fifth Avenue for housing the photographic equipment. Thanks also are due to Mr. Neave of the same organization for his fine co-operation. The author wishes especially to call attention to the part played by R. M. Partington, F. B. Headley, and A. C. Sugden, who successively operated the equipment during the three summers. The assistance of Mrs. Sugden during the 1937 season also should be mentioned. J. H. Hagenguth and C. J. Kettler deserve special mention because of their assistance in designing and building the equipment used. John Russ has been of much help in assisting in the preparation of this article. J. B. Bassett and other associates deserve the author's sincere thanks for their kind assistance in connection with this investigation.

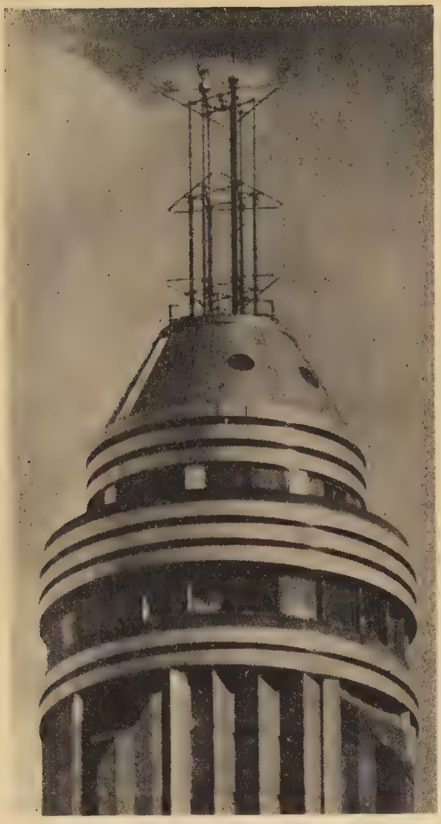


Figure 1. Antenna system atop Empire State Building; completed in this form July 1936; oscillographs connected to highest antenna

Photo courtesy *electronics*

At the insulator where the inside conductor emerges from the outer pipe, the smallest arcing distance is 1.25 inches. Obviously, for some strokes of lightning flashover will take place at the insulator, and therefore will interfere with the taking of oscillograms.

Oscillographs

Since one of the objectives of this investigation was the determination of wave shape, the cathode-ray oscillograph was arranged to initiate on waves whose rate of current rise was 2,000 amperes per microsecond or faster with a crest current of 6,000 amperes or more. The cathode-ray oscillograph was designed to record, on a continuously moving film, single impulses up to 100 microseconds in duration, also any succeeding impulses of like duration where the time interval between successive discharges was at least 500 microseconds. Because of the relatively low flashover voltage of the antenna insulator, the most severe lightning strokes to the building could not be measured because of insulator flashover.

Toward the end of the 1935 season, an examination of some of the photographic results indicated that with many strokes possibly current was flowing for a relatively long time, and an oscillograph was installed designed to record continuously discharges persisting as long as one second. This oscillograph was an adaptation of the crater-lamp oscillograph[4] used in an earlier investigation, but some modifications were required since the oscillographs at the Empire State Building could be serviced only at the beginning or end of a storm. As used in New York, the crater-lamp oscillograph galvanometer was connected to the shunt in the antenna circuit at all times, the drum carrying the film being run at constant speed, so that it was necessary to supply the illumination for the optical system only when a stroke occurred. This was done through the use of a crater lamp as a light source with a suitable initiating circuit, so that recording began within 20 microseconds after initiation voltage on the shunt was reached. The film speed was such that 0.90 inch represented 0.01 second. This oscillograph was arranged so that once set in motion 14 oscillograms could be taken without attention on the part of the operator. Films from this oscillograph have been designated as slow-speed records.

The shunt used for both oscillographs consisted of the 0.03-ohm shunt already mentioned in parallel with a Thyrite shunt. Using this combination of a linear and a nonlinear resistance, currents as low as 20 amperes were indicated with the crater-lamp oscillograph with a maximum measured of 24,000 amperes. The cathode-ray oscillograph was set to record a minimum of approximately 1,000 amperes, and a maximum of 200,000 amperes.

With both oscillographs, means were provided for determining the time of the stroke, so that the results could be correlated with those obtained from the various cameras.

Magnetic Links

During 1935, magnetic links were arranged to record current flowing in the two vertical antennas which existed at that time. After the radiator shown in figure 1 was erected, the magnetic links were so placed that the current flowing in each of the seven grounded vertical pipes extending above the roof could be measured. Readings from these links would not be expected unless the insulator at the top of the pipe to which the oscillograph shunts were connected flashed over, assuming of course that the stroke made contact at the highest point above the tower, which it did in every case that was observed, save one, during the three years of study. This stroke made contact about 16 feet down from top of antenna. Although not every stroke was observed, data were obtained for the great majority. There is also a photograph by Gaty[15] that shows a discharge to a point some 60 feet from the highest point, which at the time was the north antenna of the two antennas then in use. However, the number of strokes to the building for which current measurements could not be made was very small indeed. Furthermore, there is no evidence that any stroke divided, one part contacting some other part of the building, although one stroke did first contact another much lower building, and later discharges in the same stroke made contact with the Empire State Building. Lacking evidence of sub-division, the currents measured can safely be assumed to be the total current in the stroke.

When considering magnetic-link measurements, it must be remembered that the results represent only the highest current,[16] if all the currents were of the same polarity. If the polarity reversed, either in the same discharge or between discharges, some measure of the reversal may be obtained if more than one link at different radial distances is used. In all the Empire State installations, three links were used, giving a wider range of current values and helping to determine the true value when reversal took place.

Photographic Equipment

Naturally, during the three years that photographs have been taken, there has been considerable development of the various cameras used. No attempt will be made here to describe more than briefly these cameras and their development.

During the 1935 season, the cameras were located to the west of the Empire State Building in the Nelson Tower. A Boys camera (referred to here as a high-speed Boys) made by Ross in London, was loaned by A. L. Loomis of Tuxedo Park, N. Y., and used by Lloyd and McMorris[17] to obtain the first photographs of leader strokes reported in the United States. A schematic diagram showing the operation of this camera is given in figure 2; this indicates how the use of two matched lenses and prisms allows a displacement of the image in opposite directions on the rotating film. A comparison of these two images, knowing the film speed, the focal length of the lens, and the distance to the stroke, allows a determination to be made of the velocity of the continuous leaders and the main strokes. As a rule, the stepped leaders have a sufficiently slow over-all velocity, so that a fair determination can be made without the second image. Of course, comparison could be made with a still picture, but the resolution would not be as good.

This Boys camera was operated at a film speed of 145 feet per second. Since storm activity over the Empire State Building is usually rather brief, early in 1936 a new type of camera was designed and built which would allow seven exposures to be made while maintaining full film speed. This camera has the same optical system as that shown in figure 2. It was designed for film speeds up to 344 feet per second. During 1936 it was operated at approximately 218 feet per second, which was reduced for the 1937 season to 124 feet per second, since it was found that considerable data were being lost because of the decrease in exposure time of weak portions of the stroke. To incorporate the feature of changing exposure while the film was running, it was necessary to operate with a short focal length, and 1.38 inches was adopted. A variety of different films was tried, but so-called "super-sensitive panchromatic" proved to be very satisfactory. For purposes of study, the image is greatly enlarged. With this camera are obtained the continuous-leader data and most of the stepped-leader data. Rates of propagation of the main stroke also are obtained from these so-called high-speed Boys-camera records.

To determine the sequence of multiple-stroke discharges, a slow-speed camera is necessary. For this purpose a camera was constructed using an 8- by 10-inch film holder with two matched lenses having a focal length of 3.07 inches, mounted in front—one lens centering on the center of the film, and the other revolving with a $2^7/_8$-inch radius around the center lens as an axis. During the 1935 and 1936 seasons, the center lens revolved on its own optical axis, but because of a slight distortion due to the center of revolution being slightly different from the optical axis, this camera and another similar one constructed for the 1937 season were arranged with the center lens stationary. During 1935 and 1936, this camera was operated at one revolution per second; but when it was found that an occasional multiple stroke persisted for more than one second, it was decided to operate two similar cameras—one at two revolutions per second and the other at one-half revolution per second. The two center photographs, being taken with matched lenses, could be put together to give a stereoscopic picture, since the cameras were on the same level and separated 14 inches.

Having two slow-speed cameras has proved to be very helpful in analyzing the data, the slower of the two giving better over-all data while the higher speed gives better resolution of individual discharges. Furthermore, having two cameras of the rotating-lens type makes it quite certain that for most strokes the image will be in a good position for resolution on one camera or the other.

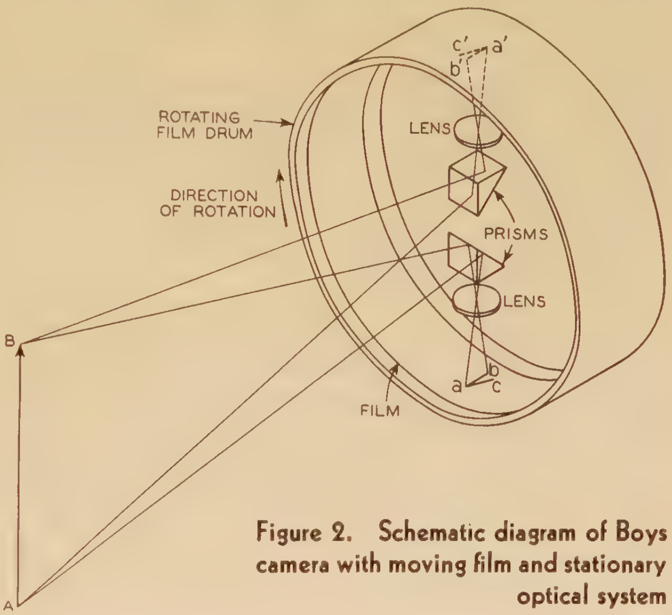


Figure 2. Schematic diagram of Boys camera with moving film and stationary optical system

Other equipment also was provided to make the mechanical work of taking the records as simple and foolproof as could be easily done. A Calculagraph was provided with which the time of operation and exposure of each camera was recorded in a manner similar to the timing of telephone toll messages. Each of the cameras had a printed form on which essential data, such as stop opening, kind of film, and other data pertinent to each camera, was recorded. The time of day and elapsed time, using the Calculagraph, was stamped on the same ticket.

An Ediphone also was provided for the recording of data, as the operator often was too busy to write down his observations. It was found, however, that the speaking tube restricted the operator too much as to freedom of motion, and during 1938 the operator used a lapel microphone, it only being necessary for him to change records, thus freeing him for other work.

Table I. Summary of Strokes by Years

					Photographs With:			
			Oscillograms					
Year	Storms	Strokes to Building	Day	Night	High-Speed Camera	Medium-Speed Camera**	Slow-Speed Camera*	Magnetic Link Records
1935	27	5					3	2
1936	26	22			5		16	2
1937	28	41	9	18	13	26	26	7

* One revolution per second in 1935–6, 1/2 revolution per second in 1937.
** Two revolutions per second in 1937.

Based upon the sound of corona and the discharges from one's fingers when standing on the small balcony near the top of the Empire State Building when storms were several miles away, it was thought that a stroke to the building could be anticipated if streamers from the building could be seen during storms at night. A careful watch was kept, and during the 1937 season the top of the building was observed through a 35-power telescope; but as was learned later, the corona streamer built up into a stroke so fast that the eye could detect no time interval between them.

During the 1936 and 1937 seasons, space was made available through the courtesy of Fletcher and Ellis, on the 56th floor of the building at 500 Fifth Avenue. This building is located ideally for studying lightning to the Empire State Building.

General Considerations

It is realized that a tall structure like the Empire State Building acts as a great needle point and may have a marked influence upon the character of the lightning discharge. It was with this thought in mind that another investigation has been carried on concurrently in Pittsfield, Mass., in an observatory specially constructed for the purpose of studying lightning. Special camera equipment has been in operation since 1935, with the idea that comparisons between strokes to the Empire State Building, and strokes to the countryside around Pittsfield, would make possible a better application of the New York data when considering transmission lines and other structures of similar height. The detailed results of the Pittsfield study cannot be given in this article, but the conclusions given here naturally will be colored to some degree by the results obtained there.

It is recognized that the photographic method has limitations as a light measuring means, particularly from the quantitative point of view. However, on all photographs taken in the last two years, each film has a sensitometer calibration, so that densities may be compared using a microdensitometer. Such an instrument is expected to be available soon for study of the records already made.

Results

During the three years of the investigation, the Empire State Building has been known to have been struck 68 times. Table I shows a summary of the strokes on which data were obtained. Nineteen oscillographic and photographic records were obtained simultaneously during 1937. No satisfactory records have been obtained with the cathode-ray oscillograph up to the end of the 1937 season.

CONTINUING STROKES

In 1935 three photographs were obtained of strokes to the building, and one of them also showed an interesting cloud-to-cloud stroke. In figure 3 is a stroke to the building showing several initial discharges followed by a period of varying but continuous illumination, with three rather considerable increases in intensity. This photograph led the author to believe that the continuing illumination was not due to effects following the initial stroke, but represented a more or less continuous current flow. Apparently Walter[18] had the same idea in 1905, but there was no direct proof, and apparently little credence has been given to this idea since Walter's suggestion. It seemed incredible that the illumination could persist so long after the initial discharge unless current was flowing, and that at times the intensity could be even greater than the initial discharge. From a study of these photographs, it was decided to install a crater-lamp oscillograph and measure, over at least one second of time, any current that might be flowing; and since the changes in current appeared for the most part to be rather slow, it was decided that the magnetic type of oscillograph would be suitable.

The results obtained in 1937, as illustrated by figure 4, show how beautifully the oscillograms and photographs

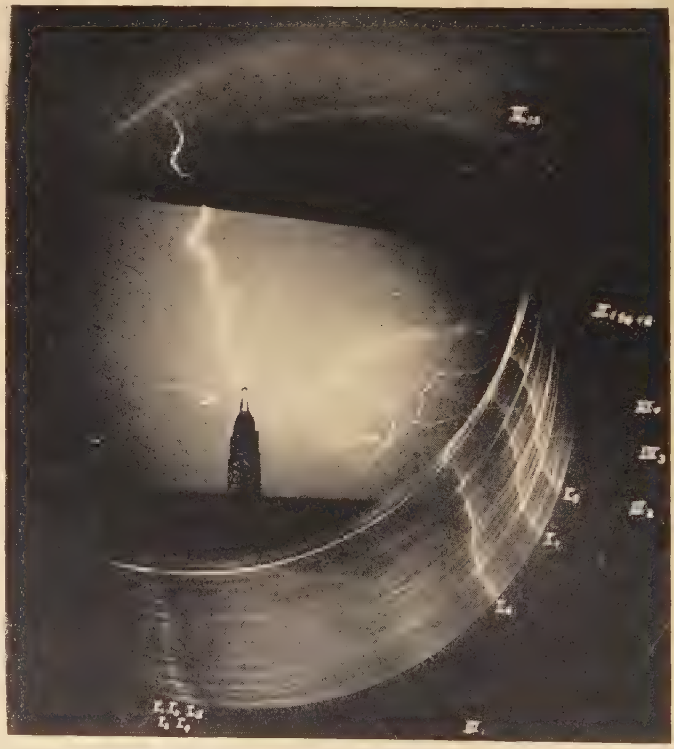


Figure 3. Stroke to Empire State Building and cloud-to-cloud discharges photographed with both still and rotating lens

I—Stroke to building. II and III—Cloud discharges check. The same oscillogram is reproduced in figure 5, being drawn to a linear current scale. It may be noticed that each change in illumination is accompanied by a corresponding change in current. In general, where there is no illumination there is no current flow; but since the camera is 2,410 feet away, a slight degree of illumination would not be recorded. Furthermore, the oscillograph could not detect currents of less than 20 amperes. Laboratory tests with a long-time discharge from a high-current impulse generator show that the illumination, using the same Boys camera, does persist as long as the current flows, even for currents as small as 0.2 ampere.

This type of stroke, in which the current flows for a relatively long period of time, has been termed a continuing stroke. It may have superimposed upon it any number of current peaks.

When the current ceases entirely for a period of 0.02 second or more and a new discharge takes place through the same path, the stroke is referred to as being multiple. Of 47 strokes photographed on either or both the medium and slow-speed cameras, 34 indicated continuous current flow until the end of the stroke, 4 consisted of two succeeding continuous discharges in the same path with a time interval between, and 7 others began as continuing strokes followed by distinct discharges. No strokes were recorded that could be called multiple strokes alone, without some admixture of continuing discharges. One stroke was observed consisting of a single discharge that was not continuing. It is possible that all the strokes would have been found to be continuing if the equipment had been capable of detecting the effects of very small currents although this does not seem likely based on present data.

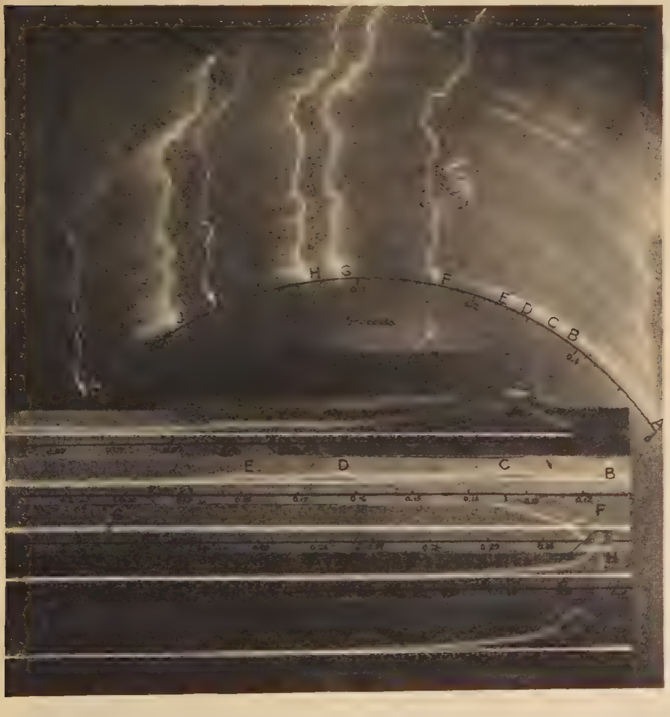


Figure 4. Multiple stroke to Empire State Building consisting of initial low-intensity long-continuing discharge and six subsequent discharges

The Boys-camera photograph was obtained from the building at 500 Fifth Avenue; oscillographic record below it was obtained in Empire State tower. Letters *A* to *K* mark corresponding points on photographic and oscillographic records

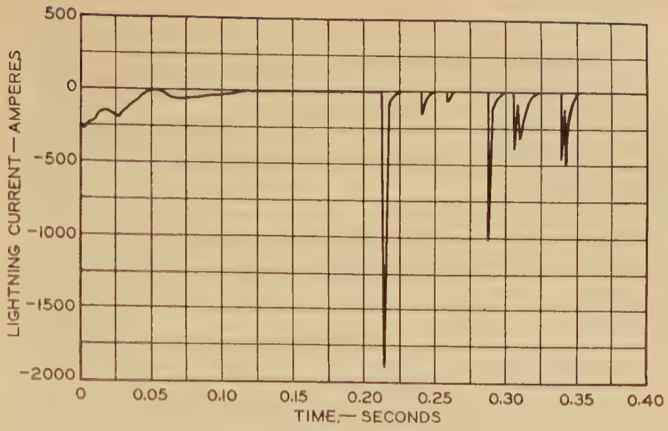


Figure 5. Replot of oscillogram of stroke shown in figure 4

These results indicate that the continuing discharge is really a d-c arc which may persist as long as 0.625 second and may have superimposed current peaks of a variety of magnitudes.

One might argue that the continuing type of stroke does not occur except to tall structures, yet once the discharge is started there seems to be little basis for assuming that the height of the building could have any great effect, except to shorten the arc, thus requiring less potential to maintain it. There is no evidence of which the author is aware to indicate that sufficient potential would not be available to maintain an arc of the increased length required to reach the ground. The ground resistance of the Empire State Building is very low, on account of the extensive foundations and pipe systems connected to its steel framework. If the cloud were a good conductor, there is no reason to believe that the discharge would be different from that of an impulse generator, to the degree that the discharge would obey the same laws, based upon the resistance, inductance, and capacitance of the circuit. But the cloud is not a continuous conductor; rather it consists of charges on drops of water separated by air gaps which must be broken down. Moreover, the cloud masses may be very large, and the charges in remote regions are not immediately available at the point of arc. The current peaks are perhaps the result of tapping new regions in the cloud separated or isolated by inhomogeneities of the cloud structure.

That the continuing type of discharge occurs to other than tall structures is evidenced by data from the Pittsfield lightning observatory, which shows many of the discharges to be of this type. Because of the relatively rather great distance of some of the strokes from the camera, continuing illumination in some cases could not be photographed even if present.

There is no doubt whatever in the mind of the author that continuing strokes are frequent to the open country, where the ground resistance may be either high or low, and that they also occur to transmission and distribution circuits where the ground resistance to d-c arc may be

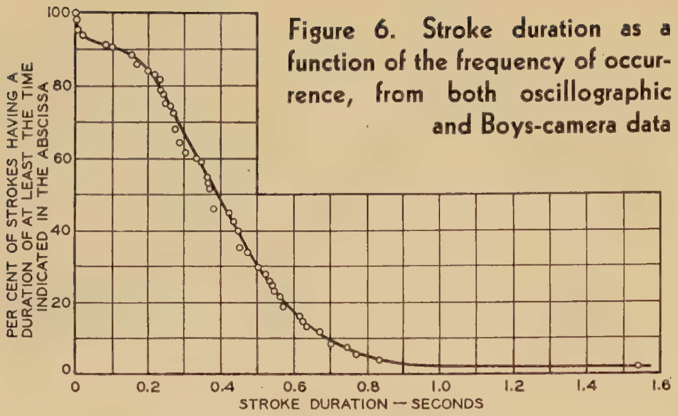


Figure 6. Stroke duration as a function of the frequency of occurrence, from both oscillographic and Boys-camera data

very low, as in a grounded-neutral system where the transformer winding represents a relatively small impedance to the flow of such unidirectional currents to ground.

Downward leaders, whether stepped or continuous, always are followed by a return discharge building up from the ground end through the established channel. With the upward stepped leaders no return stroke, as such, is found—the last streamer having extended itself to meet either a down-coming leader or streamer; current continues to flow in increased or decreased amount until the charges are so depleted that the discharge ceases. As a rule, the initial discharge of a continuing stroke is not very bright compared with discharges that may follow in the same path; however, in eight cases the photographs gave the impression of a strong upward main stroke at the beginning, but close analysis, often in conjunction with other data available, indicated that the apparent brightness was in the upward streamers—more likely the result of a succession of closely packed bright streamer tips.

Schonland, Malan, and Collens[11] suggested that the return-stroke process is dependent upon the availability of charge at the end of the leader channel, indicating that discharges into the air did not exhibit the return-stroke process because of a lack of charges at the end of the streamer. It would seem that the same explanation would account in part at least for the lack of return stroke process when a discharge proceeds from earth to cloud, that is, sufficient cloud charge is not immediately available to produce the return stroke.

Duration of Discharges in Same Path

The maximum duration of any stroke measured during the three years of study was 1.53 seconds, which is considerably longer than any reported heretofore. This time, of course, does not represent the longest possible duration, but considering all the data of this and other investigations it probably is close to the maximum. Using data from both the crater-lamp oscillograph and the Boys cameras, the curve in figure 6 was obtained. This shows that at least 50 per cent of the discharges will have a duration of about 0.4 second.

Polarity

Of the 55 strokes studied during the three years, none are known to be initially from a positive cloud center. All magnetic-link readings indicate negative cloud, although some reversal was obtained with many of the readings. It is best, however, to give most weight to the oscillographic records, since the information they yield is of a detailed nature, although the discharges of highest magnitude were not measured on the oscillograph. Those discharges that did not flash over the antenna insulator did not give magnetic-link records, but did give oscillographic records. For those cases where the oscillograph did not record, but the magnetic links did, it is safe to state that no stroke from a positive cloud occurred, unless it were of relatively small magnitude. It is believed that during 1937 such a stroke would have produced a record on the crater-lamp oscillograph, but since none was found there appears to have been no stroke initially positive to the building.

Of the 27 strokes for which oscillograms were obtained all but three were entirely negative, that is, from negative cloud. These oscillograms show how different in detail the lightning discharge may be, and considering the infinite variations of conditions in the cloud this does not seem strange.

One of the oscillograms showing reversal in polarity of discharge is reproduced in figure 8, which is for a continuing negative stroke (number 14) of small magnitude, followed 0.064 second later by a negative discharge having a crest of about 1,500 amperes. This was followed with almost exactly the same time interval by a positive dis-

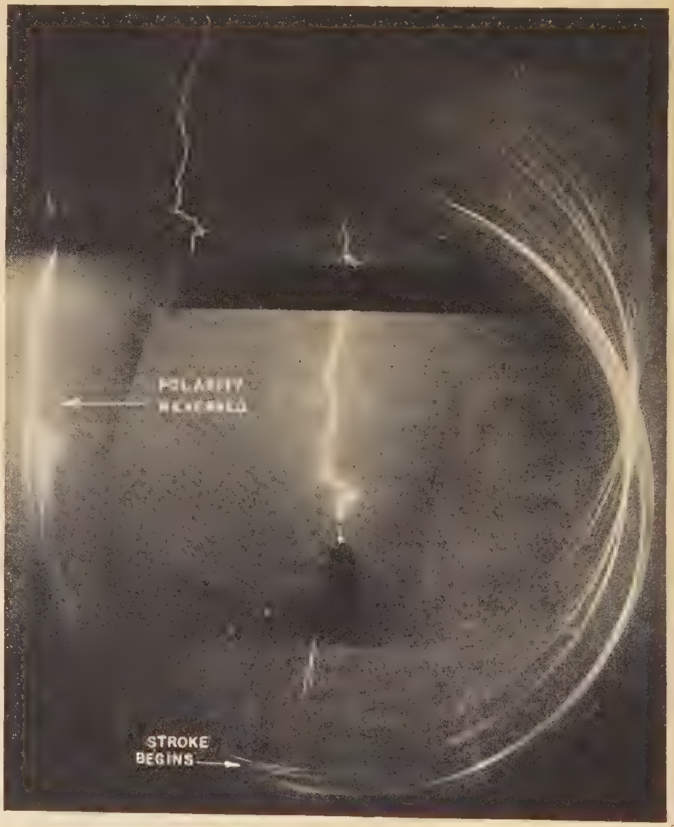


Figure 7. Multiple stroke consisting of initial long-continuing low-current discharge and two heavier discharges, last of which had positive polarity. Rotating-lens image continued for more than one revolution

charge having a crest of about 2,000 amperes and persisting a little longer than 0.03 second. The entire stroke had few current peaks, but like the other two similar strokes recorded the reversal occurred at the end.

Photographs were obtained of stroke 14 with all three cameras, the medium-speed (2 revolutions per second) record being reproduced in figure 7. This shows the beginning of the stroke at the point marked, which by the way shows photographic reversal. The noncontinuing discharge at 0.314 second had a downward continuous leader having a velocity of 9.5 feet per microsecond (medium-speed camera). The position of the image of the third and final discharge, which was positive, was such as to make the determination of whether or not it possesses a leader rather difficult. At least none could be found in spite of the most careful examination of the original films. In no other regard was it possible to detect any difference that might be ascribed to change in polarity.

The third case of reversed polarity is that of stroke 21, for which the slow-speed (one-half revolution per second) record is shown in figure 9 with corresponding oscillogram in figure 10. As with the other two this stroke began as a continuing negative stroke, changing to positive at the end. The negative crest current was 600 amperes, while the positive was a little over 900 amperes. Such a stroke would have registered as a positive stroke on a magnetic link. No leader stroke was found at the point of change of polarity, although the variations in current and the corresponding changes in intensity for approximately 0.01 second after reversal may have some significance. This is discussed under the general heading of leader strokes.

No distinguishing characteristics could be found from the slow-speed record that would identify this portion of the stroke as being positive. If the illumination died out when passing through zero current, it is not apparent on the film.

Laboratory tests on a vertical 60-cycle arc with a current of approximately two amperes showed that the illumination in general dies out when the current passes through zero. It also was noted that the illumination is not continuous between the electrodes even though the current does flow continuously. This same phenomenon is apparent in the photographs of continuous strokes of natural lightning with moving lens.

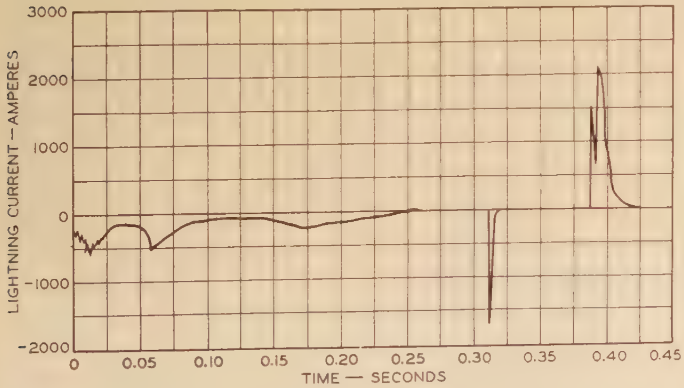


Figure 8. Replot of crater-lamp oscillogram of stroke shown in figure 7, showing reversal of polarity

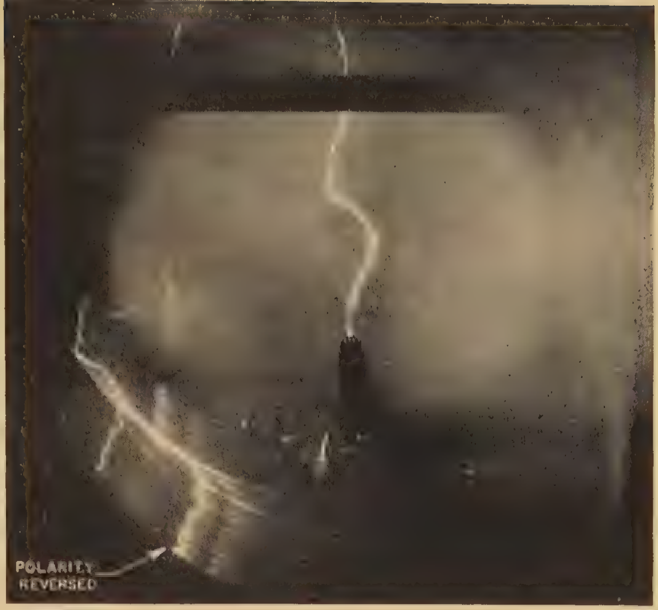


Figure 9. Heavy single continuing discharge with large number of current peaks. Stroke reversed from negative to positive at 0.11 second

Thus it appears that discharges to the building with positive cloud occur very rarely, if ever. Approximately 90 per cent of all discharges measured with the oscillograph were entirely negative. The other three strokes showing reversal began as continuing negative discharges, which seems to indicate that as the continuing discharge progressed, tapping more and more remote regions of the cloud, it finally reached an upper portion, perhaps where there was sufficient positive charges to give the results found.

AMOUNT OF CHARGE TRANSFERRED BY THE STROKE

Until these oscillographic results had been analyzed, the author[14] believed, based on the best information available, that 20 coulombs was the maximum to be expected from a single lightning stroke. However, one of the strokes recorded was found to have delivered a total charge of 164.1 coulombs, of which 2.6 coulombs resulted from the flow of positive current; this is about eight times the maximum previously estimated. Figure 11 gives the results in curve form for all the 27 strokes for which oscillograms are available. This curve indicates an expectancy of 35 coulombs or more for 50 per cent of the strokes.

Mechanism of Discharge

One of the most important contributions of this investigation to the study of lightning as a natural phenomena is the discovery in 1936 and measurement of upward leaders from the top of the building. (That upward leaders would be found was predicted by T. E. Allibone[21] in May 1938.) As a matter of fact, all the con-

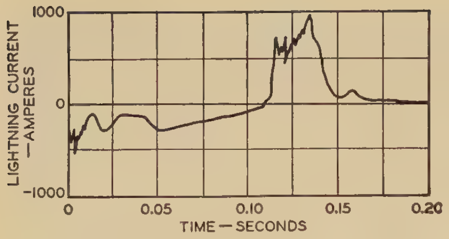


Figure 10. Replot of crater-lamp oscillogram of stroke shown in figure 9, showing reversal of polarity

tinuing strokes on which it is possible to make a good analysis show the existence of the upward stepped leader. It is nearly always visible on the slow- and medium-speed photographs when the beginning of the stroke is so located upon the film as to make analysis possible. It is difficult to measure propagation velocities on these slower-speed photographs, but over-all velocities can be obtained in many cases. The high-speed photographs also have shown some upward stepped leaders.

Seven strokes, which did not begin as continuing strokes and which had a rate of current rise steep enough to cause flashover of the antenna insulator, are all believed to have had downward initial leaders. Reliable data were obtained on 2 of these strokes.

There seems then to be two different types of strokes to the building, both negative in polarity: One is the continuing relatively low-current stroke beginning at the building and extending into the cloud; the other is like that identified by Schonland[10] where the stepped leader begins at the cloud, but this type of stroke to the building *for the cases observed* is not initially continuing and has a high rate of current rise, and presumably usually reaches a high current value before beginning to decay. Since downward and upward stepped leaders to the building, always with negative cloud polarity, have been observed, it would appear that the direction of propagation of the initial leader is not dependent upon polarity, but is dependent to a large degree upon the configuration of the two electrodes. Laboratory tests indicate that between needle and plane the discharge begins at the point, irrespective of polarity; this also has been checked by Matthias,[19] and Allibone.[21] Between two needles the discharge appears to start from each end, and this may be the case of the upward leader at the Empire State Building; but within the limit of our observation, which often extends as far as the stroke is visible, or at any rate 2,600 feet vertically, no evidence has been found of a downcoming stepped leader to meet the one coming up from the building. An intermediate condition may exist with conducting structures having heights of the order of 100 feet, such as transmission-line structures.

It is quite certain that branching takes place in the direction of propagation, and is not dependent upon polarity. This is confirmed by laboratory tests reported by Allibone and Meek[21] at reduced atmospheric pressure, as well as by unpublished work by the author. Allibone and Meek also found leaders from both electrodes when both were pointed. Most of the strokes to the Empire State Building that began with upward leaders do not show branching, but in five strokes branching upward was found. In those strokes where downward stepped leaders to the building were observed, no branching was found, although downward branching was found in strokes where stepped leaders were not recorded. In no case was downward branching found with upward stepped leaders or vice versa.

It was of much interest to find that all subsequent discharges following the initial discharge were preceded by a continuous downward leader in every stroke where a leader of any sort was found. Frequently leaders could not be found for subsequent discharges, but they may have been too weak to photograph. The fact that they are found on so many subsequent discharges would strongly indicate that they could be found on all subsequent discharges through the same path, if the limitations of recording permitted. Once the path was established, whether by upward or downward stepped leader, subsequent leaders always were downward.

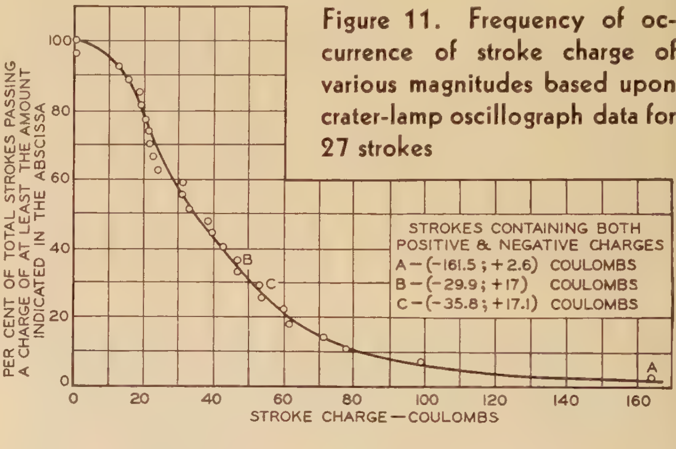


Figure 11. Frequency of occurrence of stroke charge of various magnitudes based upon crater-lamp oscillograph data for 27 strokes

The current in a continuing stroke need not reach zero in order that a discharge may occur with a continuous downward leader. One example of this kind was found, the continuing current being something less than 20 amperes when the sudden increase in current appeared. In general, downward leaders are associated with high rates of current rise, while with upward initial leaders the rate of rise is relatively slow.

In figure 12 diagrammatic sketches show the usual type of leaders to be expected, comparing a stroke to comparatively level earth with a stroke to a tall conducting object having a shape similar to that of the Empire State Building.

The author has been puzzled since first reading of the work of Schonland as to a method of attack that would allow one to measure the currents required to support the stepped leaders when fed from the cloud. When the streamers are upward and are fed from the antenna through the oscillograph shunt, the problem of measurement becomes much easier. Since the time interval between the steps as measured by the high-speed camera is of the order of 20 microseconds, only a cathode-ray oscillograph correctly would measure these streamer currents. Such equipment was installed for the 1938 season. However, the oscillograms do show a period of fluctuation during the streamer period which corresponds to a similar fluctuation in illumination at the beginning of the continuing stroke. This type of disturbance is plainly visible in figure 13.

The first streamer currents are not recorded on the crater-lamp oscillograph, but if the period of fluctuation of illumination at the beginning of the continuing stroke indicates streamer currents feeding leaders within the cloud or out of range of the cameras, then the data indicates that these currents may be of the general order of 50 to 650 amperes. The first few streamers, those feeding the portion of the leader within the range of the cameras, appear to vary from 50 to 200 amperes. Considerable interest centers around what happens with a change in polarity, but no distinguishing difference could be found.

Leaders

Of 17 strokes photographed in 1936, 13 definitely are known to have been initiated by upward stepped leaders, while during the 1937 season, out of 36 strokes to the building 23 had upward stepped leaders. The remaining 4 strokes of the 1936 season could not be identified. All those identified as upward leaders were associated with a continuing stroke. Of the 13 strokes not having upward stepped leaders measured in 1937, 2 had initial upward continuous leaders and 2 had initial downward continuous leaders with 9 remaining without sufficient data to classify. Of these 9 strokes, 5 appeared only on the oscillograph record; and because the current was less than 125 amperes, initiation was delayed, so that if the characteristic current variation during the streamer period had been present it was lost. Three of the strokes occurred during heavy fog and were recorded on the slow-speed cameras very faintly. The ninth stroke was very weak and without discernible leader. Although all upward leaders initiated continuing strokes, and all continuing strokes for which leader data are available had upward leaders, either more data will show downward stepped leaders to the building initiating continuing strokes, or it will have to be concluded that this situation is peculiar to this tall structure. (This discussion is confined to strokes in which continuous discharge followed the initial stepped leader.)

Of the records obtained of upward initial stepped leaders, those for stroke 16 perhaps are most reproducible, and at the same time complete camera and oscillographic records are available. The medium-speed photograph reproduced in figure 13 shows the stroke beginning with an upward leader, the presence of which plainly can be seen on this record, followed by an illumination that gradually dies out. This is followed by six successive discharges. The oscillogram shown in figure 14 was delayed about 0.008 second in starting, due no doubt to the small current for initiation. The current after the leader had completed its path was small, being less than 100 amperes for 0.08 second. The last two discharges which apparently are each made up of two separate discharges, appear from the oscillogram to be one discharge. This also is confirmed by the high-speed photograph.

In figure 15 is reproduced enlarged sections of the film taken from the high-speed camera for stroke 16. In the upper record may be seen the initial upward stepped leader, with a velocity of propagation of 0.98 feet per microsecond, an average interval between steps of 30.4 microseconds, and an average length of step of 25.7 feet. Each of the bright points is connected with the top of the building with a streamer which is visible on the film in nearly every case, but may not appear after reproduction. Twenty-three steps are visible. The streamers move upward from the top of the tower at a velocity of approxi-

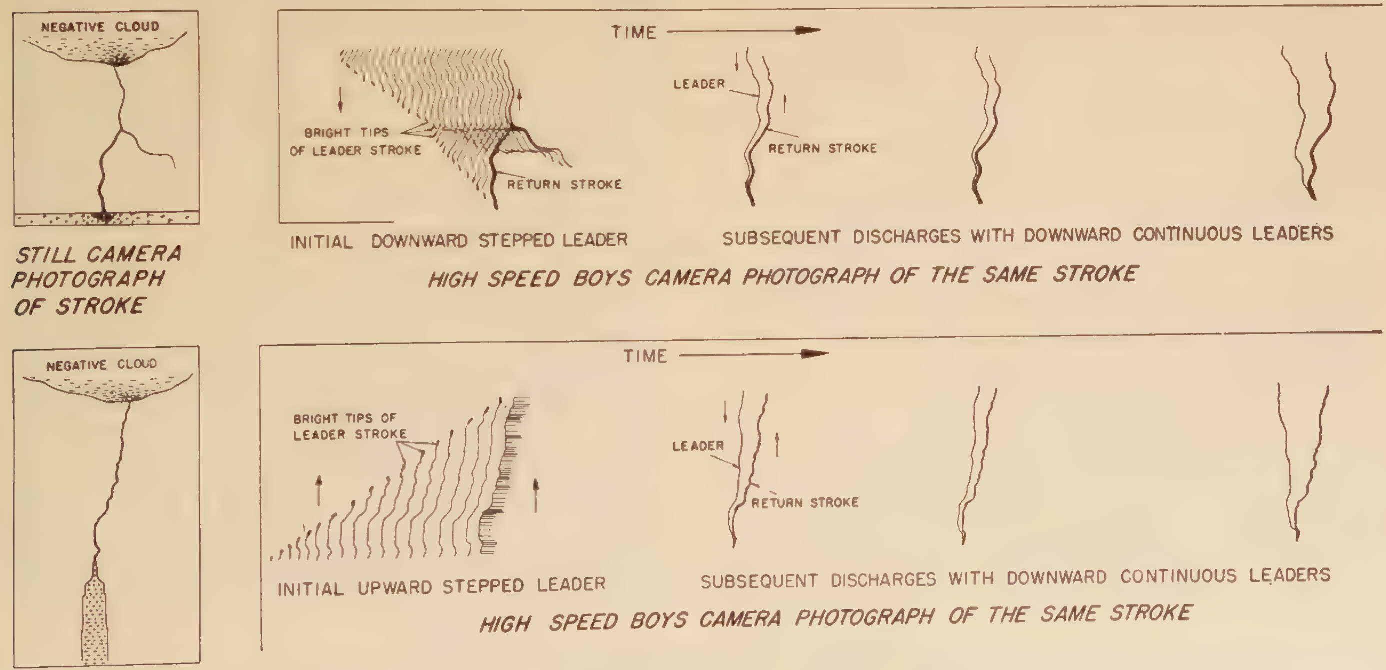

NEGATIVE CLOUD
STILL CAMERA PHOTOGRAPH OF STROKE
TIME
BRIGHT TIPS OF LEADER STROKE
RETURN STROKE
LEADER
RETURN STROKE
INITIAL DOWNWARD STEPPED LEADER
SUBSEQUENT DISCHARGES WITH DOWNWARD CONTINUOUS LEADERS
HIGH SPEED BOYS CAMERA PHOTOGRAPH OF THE SAME STROKE
NEGATIVE CLOUD
TIME
BRIGHT TIPS OF LEADER STROKE
LEADER
RETURN STROKE
INITIAL UPWARD STEPPED LEADER
SUBSEQUENT DISCHARGES WITH DOWNWARD CONTINUOUS LEADERS
HIGH SPEED BOYS CAMERA PHOTOGRAPH OF THE SAME STROKE
STILL CAMERA PHOTOGRAPH OF STROKE

Figure 12. Schematic diagrams showing discharges from negative cloud to substantially flat terrain (upper) and to tall structures (lower). A few downward stepped leaders have been observed to the Empire State Building

mately 200 feet per microsecond. Almost all the streamers retard slightly as they approach the end of their travel, as evidenced by a change in slope of the streamer as drawn out along a time scale by the motion of the film.

No relation could be found between the length of step and the time interval. The minimum length of step was 19 feet and the maximum 69 feet. Most of the steps were close to the average of 25 feet, but considerable error can take place in this measurement, both on account of the smallness of the image and the variations of path in the line of sight. There is no proof that the steps are not substantially constant in length.

Although the time interval varied from 100 to 20 microseconds, most of the measurements were close to the average of 30 microseconds. The accuracy of these measurements is probably somewhat better than of those involving the length of step.

The six following discharges are reproduced in the lower portion of figure 13. Each has a continuous leader, the velocities of which were as follows in the order given: 16, 33, 50, 73, 45, and 44 feet per microsecond.

Upward-stepped-leader velocities ranged from 0.17 to 2.09 feet per microsecond while downward-continuous-leader velocities ranged from 1.9 to 128 feet per microsecond. Although an effort was made to determine if any relation existed between the amount of charge in a stroke and leader characteristics, none could be found with the data available. Likewise the time interval between succeeding discharges could not be related definitely to the velocity of propagation of downward leaders. More data may show some relation between these factors.

Deionization Time

There seems to be few data that would help fix the time required for the air to restore itself to its original insulation value. Perhaps the longest time for a lightning stroke between discharges in the same path would give some indication of the deionization time, assuming of course, that the current from the preceding discharge was zero during the interval. If the illumination streaks on the slow- and medium-speed records are used as indications of current flow, which has been the practice in preparing this article the longest interval of time during which the current was zero was 0.22 second. (The longest interval measured in Pittsfield was 0.44 second.)

One might think that wind velocity would have something to do with deionization, but many cases are on record where the path has been blown along by the wind, and at least in those cases the path was sufficiently ionized that the discharges still continued in substantially the same path. In a 60-mile wind, the path would move 17.6 feet in 0.2 second. Since the displacement at the electrodes is so small compared with the length of the arc, it is doubtful if the wind has much effect. When sufficient data are available, a relation may be found between the amount of current and its duration, which has an influence upon the time that the path remains ionized.

Branching

Although no statement can be made on data taken in the New York investigation concerning the effect of polarity on branching, yet with negative cloud, branching has been found both upward and downward, depending upon the direction of propagation. Six of the 27 photographed strokes to the Empire State Building secured in 1937, show branching, four being branched upward and two downward, with corresponding upward and downward initial leaders.

In general, the character of the downward branching is quite different from that of upward branching, appearing as rather short branches only a few hundred feet apart, measured along the main stroke channel. Frequently the upward branches reach out to cover a considerable area, although this is not certainly true in every case recorded. In the case of the path immediately adjacent, no division was recorded closer than 600 feet from the top of the building.

If direction of branching can be taken as an indication of the direction of propagation, in the many cases where still photographs are available but no moving-film records have been taken, considerable progress will have been made in the analysis of wave shapes of lightning current reaching transmission lines and similar structures, assuming that the rate of propagation and amount of charge determine the wave front and crest current.

Maximum Currents Measured

Table II shows the values of current measured with the magnetic links during the four years they have been in use.

In figure 16 is plotted the frequency of occurrence of currents of various magnitudes, whether measured by the oscillograph or through the use of magnetic links. Plotted with this curve is one taken from the most recent data of Lewis and Foust[2] for transmission lines, and from McEachron and McMorris[22] for currents through lightning arresters connected to distribution circuits.

Discharge Path

Since the electrostatic field is along smooth curved lines, it is very evident that lightning, and for that matter sparks in general, do not follow the direction of the field. This is because breakdown is not simultaneous over the length of the path, and the progressing streamer picks out the best path from instant to instant, resulting in the crooked path so familiar to one who studies lightning. This being so, it is not difficult to visualize why lightning does not always strike the highest object. Where upward leaders determine the path, the stroke presumably will be from the highest point. However, with downward leaders, the best path may not be the shortest path, and the attractiveness of one path over another may change even during the progress of a multiple stroke.

The first stroke of this type to the Empire State Building to be photographed is shown in figure 17 and was taken in August 1936. Two strokes to the building appear in this record, the camera having been moved between them. Unfortunately at the time the stroke on the left occurred the moving lens had closed so no detailed record is available of what happened. However, the record from the still lens tells an interesting story. The path of the stroke is displaced sufficiently so that four discharges may be seen. The first discharge of the series struck a building 360 feet high and 1,200 feet west of the Empire State Building. Since this first discharge is branched downward, presumably in the light of present knowledge, it had a downward leader. The three following discharges left the path of the first discharge at a point 655 feet above the Empire State Building, the first discharge to reach that building showing at least one downward branch approximately 550 feet above the building. The remaining discharges had no branches that could be detected. It may be that a streamer built up from the Empire State Building which changed the course of the succeeding discharges, but there is no evidence to support this idea except that it is what one would expect.

Out of a total of 46 strokes recorded to the building, no stroke has terminated within a cone whose base radius on the ground is 1,200 feet, except one which terminated 16 feet down from the top of the antenna. The Gaty[15] photograph referred to in the beginning of this article is the only other known stroke that failed to strike the top and struck within the cone.

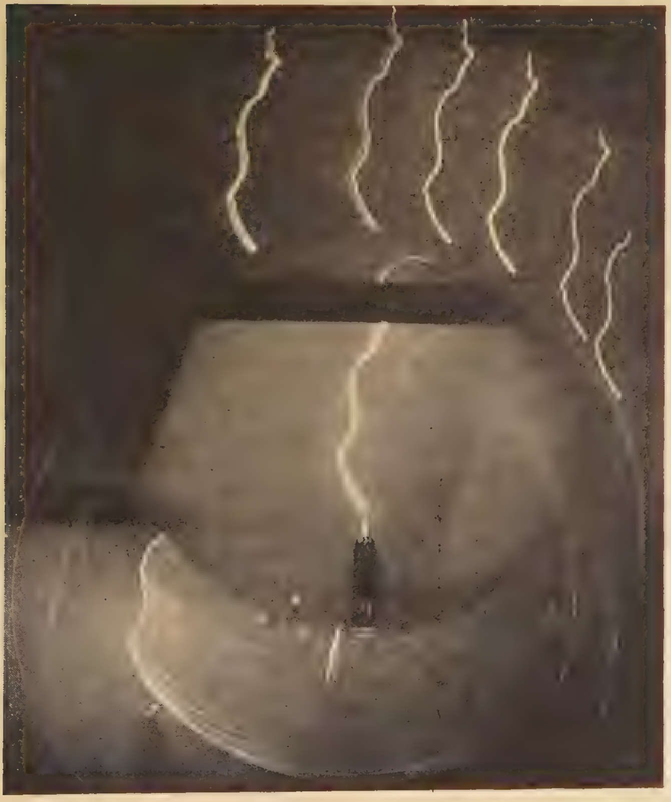


Figure 13. Multiple stroke consisting of long-continuing low-current discharge followed by six noncontinuing discharges. Arrow indicates point at which oscillograph started to record

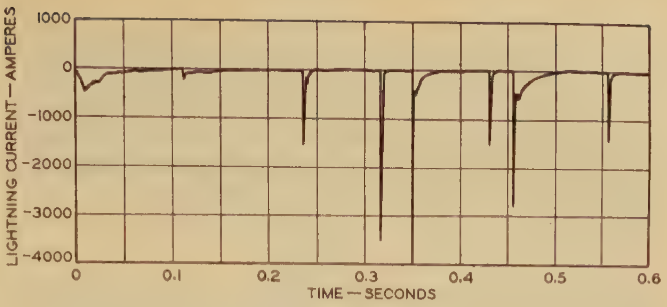


Figure 14. Replotted oscillogram of stroke shown in figures 13 and 15, showing seven discharges for each of which a leader was found

Upward Streamers Without Connecting Stroke

Two upward streamers from the Empire State Building that did not result in a stroke to the building were photographed in 1937. One of these was about 300 feet long, and apparently took place at the time of a cloud-to-cloud discharge. Details are lacking on account of the poor visibility at the time. The other streamer occurred at the time of a single cloud-to-cloud discharge when a branch downward came within 400 feet of the top of the building. The upward streamer from the building top extended to within 130 feet of the downward branch.

One upward streamer also was photographed in 1936 extending 85 feet upward from the Metropolitan Life Insurance Building which is a structure 657 feet high and situated 2,100 feet from the Empire State Building. The same film also shows a stroke with upward leader from the Empire State and one with an upward leader from the Cities Service Building.

Thunder

During 1935 the engineer operating the camera reported that on two occasions he saw strokes to the Empire State Building, but did not hear thunder as it usually is identified. He reported a sound that he described as being the same as though a paper bag full of water had been dropped for a short distance. Upon further investigation it was recalled that the Superintendent of Buildings in Washington, D. C., had reported[24] that in 1885 lightning struck the Washington Monument without audible thunder. In the light of what is known now, it appears that lightning without the usual thunder will result from the upward streamer of small magnitude followed by a continuing stroke without any steep current peaks. Such a continuing stroke, which is really a d-c arc, might well give the appearance of a severe stroke of lightning without much, if any, thunder in the ordinary sense. In many cases during the 1936–37 seasons, the noise of the high-speed cameras was such that observations on thunder were often unsatisfactory.

Streamer Currents

The velocities of upward stepped leaders fall within the limits measured by Schonland for downward stepped

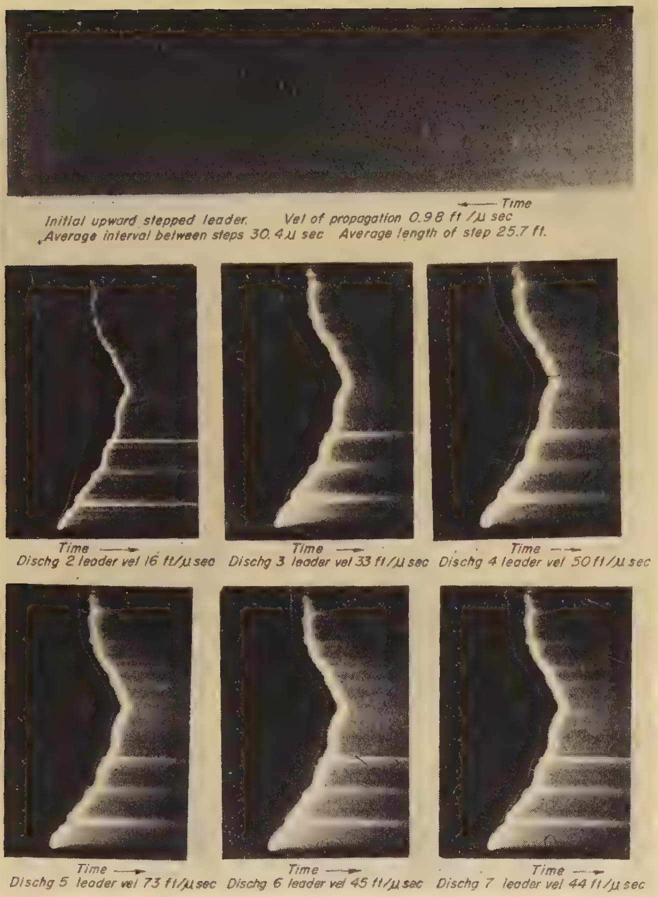

← Time
Initial upward stepped leader. Vel of propagation 0.98 ft /μ sec
Average interval between steps 30.4 μ sec Average length of step 25.7 ft.
Time →
Dischg 2 leader vel 16 ft/μ sec
Time →
Dischg 3 leader vel 33 ft/μ sec
Time →
Dischg 4 leader vel 50 ft/μ sec
Time →
Dischg 5 leader vel 73 ft/μ sec
Time →
Dischg 6 leader vel 45 ft/μ sec
Time →
Dischg 7 leader vel 44 ft/μ sec

Figure 15. High-speed record of multiple stroke shown in figure 13

Top record shows progress of initial upward stepped leader. Lower records show six noncontinuing discharges, all with downward continuous leaders. Although all leaders showed plainly on the original negative, retouching was required to make them visible in the reproduction

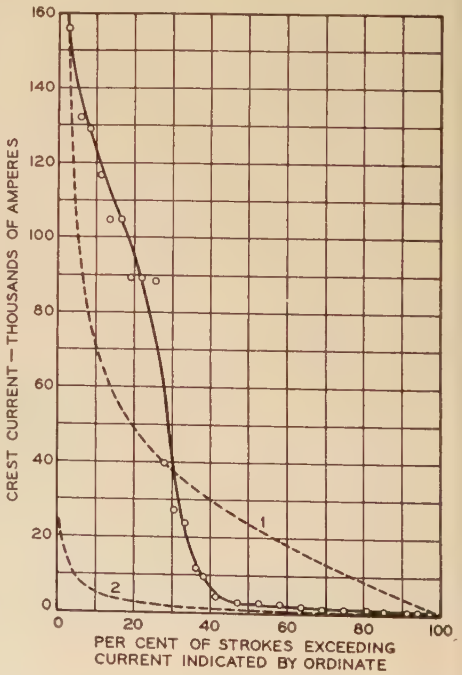
leaders, and the time intervals are of the same general order of magnitude. The downward continuous leaders had velocities also within the limits obtained by Schonland and ourselves when measuring strokes to open country. These comparisons lead one to believe that as a first approximation the streamer currents from the top of the building will be of the same order of magnitude as those that move downward from the cloud in the stepped leader.

A consideration of the data seems to indicate that the stepped leader has about the same characteristics whether upward from a well-grounded building or downward from a cloud having charges residing upon the surface of drops of water or ice particles more or less insulated from each other. Since the lack of mobility of charges within the cloud will have but little effect upon the mobility of charges in the earth, it is reasonable to conclude that the mechanism of the stepped leader is not peculiar to the cloud and its formation, but would have existed if the cloud had been a conducting body with a point of concentration provided by a long conducting needle pointing toward the earth.

Considering the upward and downward leaders from another point of view, as seen from the earth end a downward leader attached to the cloud through a streamer starts an upward moving main stroke following contact with the earth. The velocity of the streamer is known, also the velocity of the returning main stroke. As viewed from the cloud end a time interval of several hundred microseconds would elapse before the main stroke reached the cloud. If conditions are the same for the upward leader one might expect a similar waiting time before the return of the main stroke, of at least half that time, if the leaders were both downward from the cloud and upward from the building. But no such time interval has been found, the last upward streamer merely becoming more intense and developing into the main stroke. What this means when applied to the downward stepped leader as viewed from the cloud end the author does not know; perhaps additional data will supply the answer.

A Picture of the Lightning Stroke

The picture of a lightning stroke as it appears to the author at present is something like the following: The majority of lightning discharges photographed in the past were branched downward, indicating downward leaders; this is to be expected when the earth is more or less a plane surface as regards the cloud, which due to its construction automatically begins to act as a needle point as the charges accumulate in some part of the cloud. The discharges proceed from the cloud in a series of steps, always being fed by a streamer from the original cloud. As this streamer progresses, choosing the best path, the charges upon the earth's surface begin to flow into the



Solid curve—Based upon 27 strokes to Empire State Building recorded by crater-lamp oscillograph and 11 magnetic-link readings

Dashed curve 1—Lewis and Foust data (reference 2) based upon 358 strokes to transmission lines

Dashed curve 2—McEachron and McMorris data (reference 22) based upon 1,608 discharges through distribution lightning arresters

Figure 16. Frequency of occurrence of strokes of various current magnitudes as determined by three different investigations

region of increased field strength due to the approaching streamer. When the field strength becomes sufficient, streamers will form from grounded objects on the earth's surface. The stroke usually will contact the longest streamer; the return stroke follows, in which charges from the earth will pass up the stroke channel, their flow constituting the current in the discharge. The shape of the front of the wave will depend upon the rate at which charges flow into the point to be struck. The crest current will be determined by the number of charges flowing into the channel at the time of contact; and if the stroke is to be continuing, charges will continue to flow until the supply is exhausted in either the earth or the cloud.

Thus the shape of the front of the wave of current of a lightning discharge with initial downward leader to a transmission line is probably dependent upon the amount of charge and the rate of its propagation toward the point to be struck, while the shape of the tail of the wave is dependent upon the amount of charge available. It is not known whether or not the percentage of continuing strokes to open country is as great as to the Empire State Building, but it is known that they do occur frequently and are probably dependent to a large degree upon the distribution of charge within the cloud for their existence. If it is true, as suggested, that the current in a discharge with a downward leader will be maximum (unless some new cloud charge is tapped) when that leader makes contact with either the earth or a short streamer from the earth, the magnitude of that current will be determined by the charge in the earth and its availability. The amount of charge in the earth will be related to the amount of charge in the cloud and so will the maximum current. A considerable portion of the charge associated with the particular stroke will move from the cloud down into the channel created by the leader. This channel of charges will extend all the way to the earth to unite with the charges from the earth when contact is made. This reasoning would lead one to believe that continuing strokes with downward leaders would be likely to have an initial peak followed by the more or less steady current flow due to the partial or complete discharge of the cloud center.

Presumably discharge starts from the cloud without being influenced much by the earth configuration, but as the discharge approaches it is influenced more and more, although as a rule that influence is local in character. However, the taller the conducting object, the greater its influence. With strokes initiated by upward leaders, the situation is different. It is believed that upward leaders will occur only when conditions on the earth simulate a needle point of sufficient height to have an influence on the propagation. Perhaps some natural configurations of the earth might be of such a nature as to produce the upward leader. However, it seems to the author safe to state that the downward leader stroke represents the type of stroke of greatest importance in the problem of protection of transmission lines and apparatus.

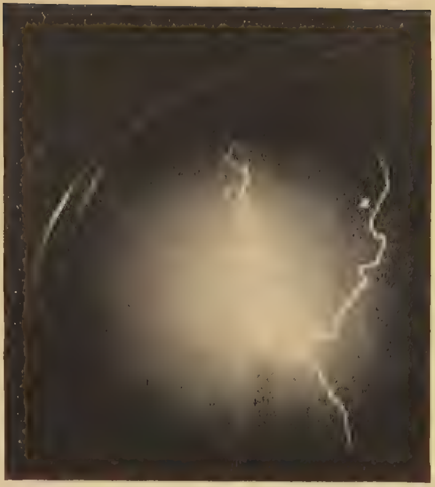

Stroke I consisted of at least four discharges; the first of the series struck a building 360 feet high and 1,200 feet west of the Empire State Building. Remaining discharges contacted Empire State Building

Figure 17. Two strokes (I and II) to the Empire State Building, the cameras having been moved between the two strokes

Table II. Maximum Currents Measured With Magnetic Links—Empire State Building, 1935 Through 1937

Date	Maximum Current (Amperes)	Number of Strokes Represented
June 27, 1935	− 27,500	1
July 19, 1935	− 40,000	2
August 23, 1936	−105,000	11
August 17, 1936	− 89,000	1
May 13, 1937	−156,000	
June 2, 1937	−117,600	
July 11, 1937	− 88,200	3
July 26, 1937	−129,500	8
August 11, 1937	− 89,600	19
August 18, 1937	−132,300	5
September 4, 1937	−105,000	6

Note: Current values indicated for 1936 and 1937 represent summation of all current values measured in the different parallel paths represented by the antenna structure on top of the building.

The effect of the continuing type of stroke must be determined. It does not seem to be of great importance on grounded neutral electrical systems, because the continuous current readily can flow to ground through the transformer windings. The isolated-neutral system may have trouble with protective apparatus connected to ground. Just how important this matter of continuing strokes will prove to be is not known at present, but it may help explain some of the failures of lightning arresters attributed to arcing grounds or other system disturbances. The continuing type of discharge may have considerable effect on the blowing of fuses used to protect distribution transformers when operating with grounded neutral.

The amount of charge involved in the continuing stroke gives some idea of the amount of charge in a cloud center. Assuming a crest current of 200,000 amperes and a time to half value of 50 microseconds, the charge would be but twenty coulombs, which is less than the average obtained in New York. However, this difference is to be noted: These large amounts of charge result from the relatively long times involved, which possibly suggests that only a part of this charge would be available for a high-current short-time discharge. All this indicates the extreme im-

(*Concluded on page 507*)

Value of the AIEE to Electrical Engineers

By JOHN C. PARKER
PRESIDENT AIEE

The greatest values of the Institute to its membership "are to be found, as elsewhere in life, through the opportunities offered for giving out rather than for taking in"

IT IS bromidic to say that the value of such an organization as the American Institute of Electrical Engineers to its membership is measured by the extent to which the member puts himself into the activities of the organization. There is, nonetheless, some value in the reiteration of these things that are well known.

It is true that the Institute sends monthly to the membership our professional magazine, ELECTRICAL ENGINEERING, which carries the news of the profession and a remarkable group of professional papers of the highest quality, and that the Institute makes available to its membership TRANSACTIONS which constitute an extraordinarily valuable reference library. If these publications merely find their way to the library shelves or into the wastepaper basket, they discharge perhaps a negative economic function. When used, they become a powerful instrument of that self-education which, in some form or other, any professional man must carry as long as he wills to grow in his profession.

Valuable as are these publications, I think they mark the least of the values of the Institute to its membership, the greatest of which are to be found, as elsewhere in life, through the opportunities offered for giving out rather than for taking in. The Institute will realize its fullest value to the membership when as many as possible of the 15,000 members are participating in some way or other in the conduct of their professional organization.

It would be difficult to stress too highly the value to those members who are creatively minded of preparing papers for presentation at the meetings of the Institute, large or small, formal or the most casual. The man who is doing things in his profession benefits much by organizing and appraising his own mental processes and presenting his ideas for the criticism of others. Those members who do not feel that they have as yet any major contributions to offer can still do a vitally creative thing in submitting written discussions.

In a larger and more generous way, this contribution to the technical proceedings of the Institute gives a man opportunity for growth in his profession which he cannot get merely out of the everyday performance of his own work, however good that may be.

In a narrower and more selfish sense, the floors of the Section meetings and the pages of the Institute publications give members an opportunity to make themselves known for what they are. I do not suggest that in professional advancement dressing the show window will take the place of solid merit, or that the returns from such participation in Institute activities will be immediate; but I do know that sound professional repute is based on just such opportunities for out-giving as the Institute offers.

Exclusive of duplications, 513 members of the Institute are engaged in the work of the general and technical committees of the national organization. I do not know how many hundreds are similarly engaged in the work of the Sections and Branches. Here again is an opportunity for the development and demonstration of administrative ability and of those personal qualities of co-operation that cannot but redound to the benefit of those men, particularly the younger ones, who show a capacity for selfless devotion to something bigger than immediate self-interest.

It is the hope and earnest intention of your officers that constructive means may be found whereby, in the various personal contacts offered by the Institute, the younger members may find opportunity to express themselves, and at the same time whereby the means may be created to bring the older members, even those in executive rather than in technical jobs, to the meetings of the Sections as well as to the major meetings. This at once should give the younger members an opportunity to know something of the kind of men who are building our profession and give these elders a chance to watch their successors perform. The mutual benefit of this is fairly obvious.

This much has to do with the narrower values that the individual engineer may, for himself, find in the Institute. There are other less tangible, but more real, values.

No man can hope to make a place for himself in society through the practice of a profession excepting as that profession takes a high and valued place in the social order. No profession can take a very large place in society except as the individual members make it strong and worthy of respect. Here in the Institute we have a great organization for mutual effort not only in promoting a better understanding and a fuller knowledge of engineering theory and practice, but of so directing that practice and giving it such a tone as will command more fully the respect of the world at large.

The Institute has been very jealous of its repute for a high quality in its publications and discussions, but even more for the highest of quality in its membership. I believe that that repute is a very real thing and that it has a wide acceptance. With the interchange of ideas and with the quiet expression of aspirations among a highly selected membership, the Institute can continue to do great things toward giving such social direction and emphasis to the work of the engineer as shall enable each of

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An address presented at a meeting of the AIEE New York Section, October 19, 1938.

us to take an increasing pride and satisfaction in his professional associations.

This modern world is industrial to its core. The spring of industry is in the mind and in the spirit of the engineer. Whether an industrial civilization shall advance the human race or shall be a period of retrogression depends in no small measure on the ethical, the professional, may I say the spiritual, attitude of the engineer toward his work and toward the society in which he lives.

Here in the Institute, men of varied occupations in enterprises having to do with engineering find a common meeting place in which, incidentally to technical discussions and to administrative responsibilities for the conduct of the Institute, they may find opportunity to appraise, to stimulate, and to appropriate the highest visions of our profession and of its place in the slow and painful upward progress of mankind. This sort of co-operative effort is too subtle for legislative administration or for resounding resolutions. It may be even too delicate a thing for formal discussions, but I am sure that in the unconscious word dropped here or there in committee meetings, in the implicit sense of responsibility and obligation as it develops in board meetings, even in the fellowship of smokers and dinner-dances, all of us can find incentives to the highest of which we are capable—and deterrents from the lowest—through our daily work to do an honest job as electrical engineers devoted to the service of mankind.

Lightning to the Empire State Building

(*Continued from page 505*)

portance of measuring the characteristics of the down-leader type of stroke. Several of these occurred to the Empire State Building during 1937, but in all cases but perhaps one, flashover of the antenna insulator resulted.

It is also important to determine the streamer currents more accurately, which will be done in the future using a cathode-ray oscillograph instead of the magnetic oscillograph. It is also planned to attempt a correlation between the photographic intensity and the current in the stroke. If practicable, this would greatly extend the field of the observations.

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Basic Equations for Electric and Sound Radiation

THE purpose of this paper* is to derive the basic equations for electric radiation and for sound radiation by elementary calculus, without using the notions of differential equations or of vector analysis. The essential step is the selection of an elementary wave pulse discontinuous only at its front and not involving double layers nor regions of infinite energy at the wave front.

The procedure for electric radiation is to assume an elementary wave pulse having a certain current distribution; thence to find the distributions of magnetic intensity and electric intensity employing the law of magnetomotive force, the law that dielectric current is the time derivative of dielectric flux, and the proportionalities between the two intensities and their flux densities, as given by the proportionality factors for the medium; and finally to show that the remaining fundamental law, that of induced voltage, is everywhere satisfied.

The procedure for sound radiation in a gas is like that for electric radiation: to assume an elementary wave pulse having a certain distribution of rate of flow; thence to find the distributions of particle velocity and excess pressure, and finally to show that the remaining fundamental law, Newton's law, is everywhere satisfied.

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* Abstract of 1938 AIEE summer convention paper number 38-92, by Alan Hazeltine (F'35), which will be published in full in Transactions.

News

Of Institute and Related Activities

Preliminary Plans Foretell Excellent Program for 1939 AIEE Winter Convention

TO PROVIDE interest for the greatest number of members a broad technical program of current interest and two general sessions have been proposed for the 1939 AIEE winter convention, which will be held in New York, N. Y., January 23–27, with headquarters in the Engineering Societies Building. Social events are being planned for the evenings—a smoker, presentation ceremonies for the Edison and John Fritz medals, and a dinner-dance. In addition, inspection trips will be arranged to a number of places of interest in the city and its environs. As in the past two years, an all-expense post-convention trip to Bermuda also is being planned.

One of the general sessions will deal with economic and social problems, which have proved to be of great interest to electrical engineers. Arrangements have been made for an address "Enterprise and Social Progress" to be given by Virgil Jordan, president, National Industrial Conference Board, Inc. Plans for the second general session have not been completed, but negotiations are under way for a speaker of national repute who will address the session on a subject of wide general interest.

Technical Sessions

As announced in the October issue, the technical program of the convention will include a symposium on rating and temperature limits of small power apparatus, which will be of outstanding interest to all manufacturers and designers of small motors as well as to those who furnish the insulating materials and to the users of the equipment. Tentative plans are that this symposium will embrace three sessions.

Other technical sessions that have been proposed embrace practically the whole gamut of Institute technical activities, as follows: electronics, protective devices, instruments and measurements, power generation, cable developments, power transmission, switching transients, communication, basic sciences, research, transportation, industrial power applications, and electric welding.

Further details pertaining to the program will be announced in the January 1939 issue.

Virgil Jordan, Noted Economist to Address General Session

By both training and experience, Doctor Virgil Jordan is eminently qualified to speak on the subject "Enterprise and Social Progress." A native (1892) of Olean, N. Y., he received the degree of bachelor of science from the College of the City of New York in 1912, and afterwards did postgraduate work in economics at the University of Wisconsin, Columbia University, and foreign universities. He taught economics at the University of Wisconsin from 1912 to 1914, and thereafter served as associate editor and special writer on economic and sociological subjects with *Everybody's Magazine* until 1920. From 1920 until 1929 he was chief economist and editor of publications of the National Industrial Conference Board, but in 1929 he became economist for the McGraw-Hill publications. In December 1932 he returned to the National Industrial Conference Board as president of that body, which position he still holds.

Virgil Jordan
A winter-convention speaker

The National Industrial Conference Board is a private co-operative, non-profit scientific institution, devoted to promoting the property and security of the people of the United States by assisting in the effective operation and development of productive industry. Its function is to discover, assemble, analyze, interpret, and disseminate accurate, complete, and useful information regarding economic conditions in the United States and other countries.

Doctor Jordan has made numerous contributions to the literature of his specialty in popular and scientific periodicals, and in the publications of the Conference Board. He is a member of the American Economic Association and of the American Statistical Association, and a fellow of the Royal Economic Society of London, England.

Symposium on Apparatus Ratings of Far Reaching Importance

With the stipulated purpose of providing information upon which revisions in AIEE standards may be based, the symposium on ratings and temperature limits of small power apparatus is expected to be of far reaching importance to manufacturers and users of such equipment. Broadly, the purpose of the symposium is to review the fundamental properties of insulating materials on which AIEE standard temperature limits are based; to discuss improved means of measuring temperatures, enabling these limits to be complied with more exactly; and to discuss principles of rating for both continuous and intermittent loading conditions.

The origin of this discussion and of the need for revisions in the present standards lies chiefly in the rapid development of the refrigeration and air-conditioning industries during the past 10 years. In these industries, motors are used to drive compressors with automatic control which provides alternating on and off periods the relative duration of which varies with the temperature and the load requirements. The characteristics of compressors require certain ratios of starting, accelerating, and operating torques, which differ materially from the values specified in the standards for general-purpose motors. These differences together with the intermittent- rather than continuous-duty service, have led to operating loads and temperatures in excess of motor nameplate ratings. The need is evident on this basis for reconsideration of the motor-torque ratios in the present standards, and for provision of operating recommendations for standard motors used in intermittent-duty applications. Another important factor is the recent development of new insulating materials that may have different temperature endurance from that of materials provided for in the present standards.

Of the three sessions tentatively scheduled, it is proposed that the first deal with the temperature limits of insulating materials and include three formal papers. One of these would show test results taken over a period of from two to three years on the temperature-life characteristics of class *A* insulation. (Class *A* insulation consists of cotton, silk, paper, and similar organic materials impregnated or immersed in oil; also, enamel as applied to conductors.) The other two papers would deal with the temperature and life characteristics of class *A* insulating materials under oil, and with the characteristics of fiber-glass insulation. Following discussion of these papers, the session would be resolved into an informal conference, and several prepared discussions are proposed on other phases of the subject. It is expected that in these informal discussions recent progress in synthetic varnishes and resins will be reported. Such materials not only play a large part in the determination of the permissible temperature for class *A* insulation, but also are limiting features in the use of class *B* insulation, especially for glass. (Class *B* insulation consists of inorganic material such as mica and asbestos in built-up form combined with binding substances.) Whether or not these synthetic materials have sufficiently longer life at high temperature to warrant new limits being set for them in the standards will be discussed, and it is hoped that new test procedures and other methods of evaluation of life-temperature characteristics will be suggested as a result.

A second technical session is proposed to cover motor-testing methods and is expected to include three papers. The first two papers would deal with methods of measuring temperatures on motors of various types, special attention being given to totally enclosed and other protected types of motors which so rapidly are growing in importance. The third paper would present a new method of measuring stray-load losses of polyphase induction motors that permits of greater convenience and accuracy than present common methods. If this new test method proves acceptable, it is expected to be included in the next revision of the AIEE test code. Following discussions of these papers, this session also would be resolved into an informal conference, at which the subject of the third session will be introduced by informal speakers.

It is proposed that the third and final session of the symposium deal with principles of rating of apparatus, and include five papers. The first of these would give a broad review of the factors to be considered in establishing rating limits of apparatus, including the history of previous work in this field. The second would deal with the principles of rating of general-purpose motors, and propose a modified temperature-breakdown torque system of rating intermediate between the present temperature system of transformer rating and the stalling torque system generally employed for mechanical apparatus. A third paper would deal with the rating and application of motors specifically for refrigeration and air-conditioning purposes. Another paper is proposed to deal with the rating of motors used on short-time duty cycles, including frequent starting or reversing. The final paper would deal with the effects of temperature on the mechanical performance of rotating machinery, showing some of the limitations due to bearing performance, expansion and contraction of insulation, and other factors that must be overcome before much higher temperatures can be employed economically in general industrial service.

Further details pertaining to the program of this symposium will be announced later.

WINTER-CONVENTION COMMITTEE

The personnel of the 1939 winter-convention committee is as follows: T. F. Barton, *chairman;* G. E. Dean, E. E. Dorting, F. M. Farmer, L. C. Miller, H. S. Osborne, J. H. Pilkington, A. L. Powell, C. S. Purnell, George Sutherland, and W. W. Truran.

Medals Awarded by AWS. The Samuel Wylie Miller Award and the J. F. Lincoln Award of the American Welding Society were presented at the opening session of the 1938 annual meeting of the society, October 17. The Miller medal was presented to J. W. Meadowcroft, of the Edward G. Budd Manufacturing Company, Philadelphia, Pa. The Lincoln Award was made in duplicate to J. C. Hodge and C. R. Sadler, of The Babcock and Wilcox Company, New York, N. Y., for a joint paper entitled "Weldability and Properties of Materials for Casing Strings."

Portions of downtown Brooklyn and New York showing the Hudson Avenue (Brooklyn) generating station of the Consolidated Edison System, the Manhattan and Brooklyn Bridges, and the downtown New York skyline in the background

AIEE Board of Directors Meets at Institute Headquarters

THE regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, on October 25, 1938.

There were present: *President*—John C. Parker, New York, N. Y. *Vice-Presidents*—F. C. Bolton, College Station, Tex.; Chester L. Dawes, Cambridge, Mass.; F. M. Farmer, New York, N. Y.; A. H. Lovell, Ann Arbor, Mich.; I. Melville Stein, Philadelphia, Pa.; Edwin D. Wood, Louisville, Ky. *Directors*—C. R. Beardsley, C. R. Jones, H. S. Osborne, New York, N. Y.; F. Ellis Johnson, Madison, Wis.; W. B. Kouwenhoven, Baltimore, Md.; L. R. Mapes, Chicago, Ill.; K. B. McEachron, Pittsfield, Mass.; C. A. Powel, East Pittsburgh, Pa. *National Secretary*—H. H. Henline, New York, N. Y.

Regrets were presented from Past President A. M. MacCutcheon and National Treasurer W. I. Slichter, both out of the United States.

Minutes of the board of directors meeting held on August 2, 1938, were approved.

Executive committee action, as of September 21, 1938, on applications was reported and confirmed, as follows: 2 applicants transferred and 1 elected to the grade of Fellow; 20 applicants transferred and 5 elected to the grade of Member; 31 applicants elected to the grade of Associate; 11 Students enrolled.

Reports were presented and approved of meetings of the board of examiners held on September 15 and October 20, 1938; and, upon the recommendation of that board, the following actions were taken: 2 applicants were transferred to the grade of Fellow; 8 applicants were elected to the grade of Member; 31 applicants were elected to the grade of Associate; 601 Students were enrolled.

Monthly disbursements were reported by the finance committee, and approved, as follows: August, $17,951.13; September, $16,698.46; October, $25,109.51.

A budget for the appropriation year beginning October 1, 1938, submitted by the finance committee, was adopted. (Information concerning the budget appears elsewhere in this issue.)

Dates for previously authorized District meetings, selected by the District officers concerned, were approved as follows: April 17–19, 1939, for South West District meeting, Houston, Tex.; May 3–5, 1939, for North Eastern District meeting, Springfield, Mass.; September 27–29, 1939, for Great Lakes District meeting, Minneapolis, Minn.

Consideration was given to the paragraph prescribing an interval of at least six weeks between any two meetings, contained in the statement of policy to be followed in arranging schedules of Institute meetings, which was adopted by the board of directors in April 1928. Upon the recommendation of the committee on planning and co-ordination, in view of the shorter time now required for the preparation of papers for meetings, this paragraph was changed to read as follows:

> The dates should be so arranged that there will be a suitable interval between the two meetings nearest to each other—preferably not less than three weeks.

To conform with the board's action, in August, merging three technical committees into one, Section 65 of the By-laws was amended by the deletion of the names of the committees on applications to iron and steel production, applications to mining work, and general power applications, and the addition of the name of the new committee on industrial power applications.

The board approved the following statement of scope of the committee on industrial power applications, upon the recommendation of the technical program committee:

> Treatment of all matters in which the dominant factors are the applications of electric power to industries (exclusive of applications within the central station industry, power generation, transportation, marine work, electric welding, electrochemistry and electrometallurgy, and illumination, which are functions of other designated technical committees). Such subjects as motor control—the combination of motor, control, and driven machine into a functioning unit, all applications to iron and steel production (exclusive of electric furnaces) and to mining work, together with the requirements of specialized devices, materials, or constructions peculiar to such applications, are properly within the scope of this committee.

Approval was given to a recommendation of the technical program committee that Section 93 of the By-Laws be amended, to reduce the present 90-day limit to one of 60 days, for the receipt of papers for presentation at a national meeting or convention of the Institute. It was understood that the proposed amendment will take the prescribed course for official adoption, and that in the meantime the technical program committee will proceed on the basis of the revised by-law.

Upon petition of the Muscle Shoals Section and the recommendation of the Sections and finance committees, and with the acquiescence of the Alabama Section, the board authorized the transfer of Marshall and Madison Counties, Alabama, from the territory of the Alabama Section to that of the Muscle Shoals Section.

Due to the transference of the engineering school of the University of North Carolina at Chapel Hill to the North Carolina State College at Raleigh the former University of North Carolina Branch of the Institute officially was declared terminated.

The following board members were elected to serve as members of the national nominating committee for the present year: C. R. Beardsley, F. M. Farmer, A. H. Lovell, C. A. Powel, R. W. Sorensen. A. M. MacCutcheon was designated an alternate, and the president was empowered to appoint any additional alternates that may be required.

The following representatives and alternate of the Institute on the American Engineering Council assembly were appointed for the year beginning January 1, 1939:

C. O. Bickelhaupt, *chairman*, AIEE delegation
W. H. Harrison
C. R. Jones
C. E. Stephens
H. H. Henline, *alternate*

(The fifth representative, President Parker, is serving for the administrative year of the Institute, August 1, 1938, to August 1, 1939)

R. E. Hellmund was appointed an Institute representative on the standards council of the American Standards Association for the three-year term beginning January 1, 1939, to succeed A. M. MacCutcheon, whose term will expire December 31, 1938. H. H. Henline, H. S. Osborne, and E. B. Paxton were appointed alternates on this body for the year 1939.

Consideration was given to an invitation to appoint an Honorary Member of the Institute, if feasible, as a member of the board of award of the Marston gold medal, established by Iowa State College, through the generosity of Anson Marston, a former professor of civil engineering and dean of engineering of the college—the board of award to consist of nine members, four alumni, one honorary member, each, of the American Society of Civil Engineers, American Society of Mechanical Engineers, American Institute of Chemical Engineers and AIEE, and the dean of engineering who will serve as ex-officio chairman of the board; the first appointee of the Institute to serve for two years and subsequent appointees for four years. The board of directors appointed Past President and Honorary Member Bion J. Arnold as such representative of the Institute, for the term of two years.

The board accepted an invitation of the American Society for Testing Materials for the Institute to join with others in the formation of an American co-ordinating committee on corrosion and to appoint one representative thereon. H. S. Phelps was appointed the Institute's representative.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

John Fritz Medal for 1939 Awarded to F. B. Jewett

The John Fritz Gold Medal for 1939 has been awarded to Doctor F. B. Jewett (A'03, F'12) for "vision and leadership in science, and for notable achievement in the furtherance of industrial research and development in communication." This medal, the

Future AIEE Meetings

Winter Convention
New York, N. Y., January 23–27, 1939

South West District Meeting
Houston, Texas, April 17–19, 1939

North Eastern District Meeting
Springfield, Mass., May 3–5, 1939

Summer and Pacific Coast Convention (combined)
San Francisco, Calif., June 26–30, 1939

Great Lakes District Meeting
Minneapolis, Minn., September 27–29, 1939

Middle Eastern District Meeting
Scranton, Pa., October 11–13, 1939

Summer-Convention Goers May See Exposition

MEMBERS and their families attending the AIEE summer convention in San Francisco, Calif., June 25–29, 1939, may see the results of the latest advancements in efficient and artistic treatment of interior and exterior areas, pools, and lagoons at the Golden Gate International Exposition which opens late in February 1939. Exposition engineers are already working nightly on the location and adjustment of the floodlight and other types of units to enhance the amazingly beautiful architectural features of the buildings and grounds. Over 12,000 kw in power will be required by the lighting alone.

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highest distinction bestowed jointly by the four national societies of civil, mining and metallurgical, mechanical, and electrical engineers of the United States for "notable scientific or industrial achievement," will be presented with suitable ceremonies at one of the sessions of the AIEE winter convention, to be held at New York January 23–27, 1939.

Doctor Jewett is vice-president of the American Telephone and Telegraph Company and president of Bell Telephone Laboratories, Inc., New York; he was president of the Institute 1922–23. A biographical sketch of Doctor Jewett may be found in the "Personals" section of this issue.

Award of the John Fritz Medal is made not oftener than once a year, and is without restriction on account of nationality or sex. It is a memorial to the late John Fritz, a leader in the American iron and steel industry, to whom the first medal was awarded in 1902. The present board of award is composed of 16 members, each participating society having 4 representatives. AIEE representatives (all past presidents) on the board making the present award were A. W. Berresford (A'94, F'14), J. B. Whitehead (A'00, F'12), A. M. MacCutcheon (A'12, F'26), and W. H. Harrison (A'20, F'31).

ASME Elects Officers. The American Society of Mechanical Engineers has announced the election of the following new officers for 1939: *president*, A. G. Christie, The Johns Hopkins University, Baltimore, Md.; *vice-presidents*, H. H. Snelling, Snelling and Hendricks, Washington, D. C.; W. L. Dudley, Western Blower Company, Seattle, Wash.; Alfred Iddles, Babcock and Wilcox, New York, N. Y.; and J. W. Parker, The Detroit Edison Company, Detroit, Mich. Those elected to managerships of the Society were Clarke Freeman, Manufacturers Mutual Fire Insurance Company, Providence, R. I.; W. H. Winterrowd, Franklin Railway Supply Company, Chicago, Ill.; and W. R. Woolrich, University of Texas, Austin. The new officers will assume their duties on December 9, 1938.

AIEE National and District Prizes for Papers

Provision in the Institute's 1938–39 budget has been made for cash awards to accompany the national and District prizes for initial and Branch papers to be awarded during the current year, as indicated below.

All technical papers presented before the Institute during the year are eligible under the AIEE paper prize regulations for competitive consideration for one or more of the established prizes, regardless of whether presented before a Branch meeting, a Section meeting, a District meeting, or a national convention, the several classes providing for equitable competition. With the exception of the prizes for Branch papers, both District and national prizes are awarded each spring for papers presented during the preceding calendar year. For Branch papers, both national and District prizes are awarded on the basis of the academic year, July 1 to June 30, inclusive. Suitable certificates accompany all awards.

National prizes that may be awarded annually, and those to be accompanied by cash awards during the current year, are as follows:

1. Best paper prizes:
    - *Engineering practice*
    - *Theory and research*
    - *Public relations and education*
2. Prize for initial paper ($100)
3. Prize for Branch paper ($100)

District prizes that may be awarded annually, together with the cash awards provided for the current year, are:

1. Prize for best paper
2. Prize for initial paper ($25)
3. Prize for Branch paper ($25)
4. Prize for graduate student paper

Although all papers presented are *eligible*, there is no provision for automatic consideration of papers, except that those approved by the technical program committee and presented at national conventions or District meetings will be considered by the national prize committee for the national "best paper" and the "initial paper" prizes without being offered formally for competition. All other papers for which prize consideration is desired must be *submitted* specifically for that purpose, through the District secretary for District prizes, or through the national secretary's office for the national prizes.

DEADLINE DATES

Papers to be considered for 1938 national prizes must be submitted not later than February 15, 1939. Papers to be considered for the District "best" and "initial" paper prizes must be submitted on or before February 15, 1939; for the District, Branch, and graduate student paper prizes, before July 15, 1939 (for papers presented during the academic year ending June 30, 1939). Those wishing further information may obtain a booklet entitled "National and District Prizes" by writing to AIEE Headquarters, 33 West 39th Street, New York, N. Y.

Coaxial-Cable System Changed. Tests, adjustments, and modifications of the two-megacycle coaxial-cable system between New York, N. Y., and Princeton, N. J., have been made by Bell Telephone Laboratories during the last few months. Equalizers and power-separation filters in all repeaters were modified to obtain improved characteristics, and methods of obtaining greater precision of equalization and regulation are being studied. Satisfactory test conversations were held over a circuit 2,100 miles long, which was built by looping conductors back and forth through the coaxial system a total of 20 times. This circuit consisted of four voice-frequency links in tandem. Using channels located in different parts of the frequency band between 100 and 1,900 kilocycles, the conversation passed through 64 steps of modulation in each direction and through each amplifier 20 times, giving the equivalent of 420 amplifiers in each direction.

The Institute Budget for the Year 1938-39

THE continuance of all Institute activities considered to be of the greatest benefit to the membership, and in some instances an enlargement of the present program, are provided for in the 1938–39 budget adopted by the board of directors at its meeting held on October 25, 1938.

Upon the recommendation of the finance committee that a balanced budget be adopted, and with the knowledge that the total of the required appropriations for Institute activities slightly exceeded the total revenue anticipated for the corresponding period, the board voted to make available $11,000 of the surplus of approximately $12,300 from the operations of the preceding appropriation year. This action was taken with the realization that certain expenditures provided for last year, amounting to about $5,000, have been deferred until the present year, and that the unusually large item for traveling expenses due to holding the 1939 summer convention in San Francisco did not represent a continuing expense. It was felt that a curtailment of any service to the membership this year to offset this temporary unbalance of the budget would not be justified.

Other important activities, such as Institute publications, National and District meetings, and Sections and Branches, have been appropriated for to a greater extent than reflected by the expenditures of the past year, as indicated in the accompanying budget tabulation.

Any presentation of the Institute budget, however brief, would not be complete without mention of the vital necessity for prompt and full realization of the expected revenue from membership dues, from which source is received more than two-thirds of the total income of the Institute.

Institute Income and Expenses for Year Ending September 30, 1938, and Budget for Year Ending September 30, 1939

	Actual Income and Expenses, Year Ending 9-30-38	Budget for Year Ending 9-30-39
Income		
Dues	$193,179.99	$199,000.00
Students' fees	11,922.00	11,500.00
Entrance fees	6,735.75	6,000.00
Transfer fees	1,045.00	1,000.00
Advertising	29,917.78	30,000.00
ELEC. ENGG.—non-mem. subscriptions	15,021.52	15,000.00
TRANS. subscriptions	6,224.66	6,500.00
Miscellaneous sales	10,406.61	9,000.00
Badge sales	1,821.90	1,800.00
Interest on securities	9,823.38	8,200.00
		288,000.00
Transferred from last year's surplus		11,000.00
Total	$286,098.59	$299,000.00
Expenses		
Publications:		
Text matter (ELEC. ENGG. & TRANS.)	†$70,259.87	*$72,900.00
Preprints	5,829.43	8,600.00
Advertising section	15,574.60	15,600.00
Year Book	6,482.32	6,500.00
Miscellaneous expense	1,515.80	2,000.00
Institute meetings	13,766.39	14,000.00
Institute Sections:		
Appropriations	23,174.94	24,300.00
Other expenses	5,645.72	5,800.00
Institute Branches:		
Meetings expenses	955.85	1,000.00
Other expenses	2,089.81	2,400.00
Committees:		
Edison Medal	349.96	200.00
Finance	1,600.00	1,600.00
Headquarters	90.10	250.00
Membership	7,949.53	8,350.00
Model registration law	9.48	600.00
Standards	5,830.98	7,500.00
Technical	158.52	250.00
Traveling Expenses:		
Geo. Dist. exec. committees	1,954.40	2,500.00
Section delegates to summer conv.	4,322.96	11,300.00
Counselor delegates to summer conv.	837.76	1,500.00
Dist. secys. to summer conv.	651.16	1,250.00
District Student conferences	6,430.37	6,500.00
President's appropriation	106.25	1,500.00
Vice-presidents	255.84	500.00
Board of directors	4,089.03	8,300.00
National nominating committee	1,062.55	1,050.00
AIEE representatives	10.05	100.00
Administration:		
Headquarters' salaries	34,395.22	35,000.00
Postage	4,076.52	3,800.00
Stationery & printing	3,945.74	3,800.00
Office equipment	441.13	200.00
Trav. expense, insurance, misc. supplies & services	2,795.56	3,200.00
Paper prizes	356.50	400.00
Joint activities:		
American Engineering Council	12,000.00	6,000.00
American Standards Assn.	1,500.00	1,500.00
Engrs. Council Prof. Dev.	850.00	850.00
Engg. Foundation research proj.:		
Impregnated paper insulation	....	250.00
Welding		250.00
Engg. Soc. Employment Service	1,162.56	1,763.00
Engg. Soc. Library	9,689.28	9,700.00
John Fritz Medal	50.00	260.00
United Engg. Trustees building assessment	11,005.44	11,000.00
U.S. Natl. Com. I.C.I.	300.00	300.00
Miscellaneous printing, etc.		4,100.00
Authors' reprints	1,798.71	....
Reprints of standards	1,173.83	....
Lightning Reference Book	385.34	....
Miscellaneous	409.63	....
Other expenses		
Membership badges	2,090.81	1,750.00
Text paper & env. in storage	2,397.04	....
Retirement salary	1,125.00	....
Miscellaneous	825.35	310.00
Total	$273,777.33	$290,783.00

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* Actual budget of $75,200.00 reduced by text paper inventory of $2,300.00

† Actual expense $71,318.48, including paper costs paid for previously.

Radio City Music Hall in New York City has been an attraction to those attending AIEE winter conventions ever since it was completed. This view shows the staircase in the grand foyer, with mirrors three stories high, and Ezra Winter's mural "The Fountain of Youth." Each of the two chandeliers is 29 feet long and weighs approximately two tons

District 7 Award for Branch Paper

Prize for Branch paper in the AIEE South West District has been awarded to Harry N. Stafford, Enrolled Student of Eastland, Tex., for his paper "The Effect of Current-Wave Distortion on Energy Measurement," presented at a student convention at the University of Kansas, Manhattan, April 15, 1938. The award was made in accordance with the prize rules as given in the April 1937 issue of ELECTRICAL ENGINEERING, page 492.

NRC Insulation Conference Held at Pittsburgh

Bringing together dielectric experts from educational institutions, research laboratories, electrical manufacturers, and equipment users, the conference on electrical insulation of the National Research Council division of engineering and industrial research held its eleventh annual meeting November 3–4, at Pittsburgh, Pa. Official registration totalled 111. Some 20 papers on a wide variety of dielectric subjects were presented during the three technical sessions. Brief digests of these papers are scheduled for inclusion in a future issue.

Following the preliminaries at the opening session, J. B. Whitehead (A'00, F'12) chairman of the conference since its organization, presented his annual report, in which he reviewed the work of the conference during the past year. He also outlined the activities of the various committees during the year, as follows:

Committee on Physics. The committee on physics held a successful meeting in Washington, D. C., during the spring meeting of the American Physical Society. A feature of this meeting was the participation of the subcommittee on electrical measurements of glass of committee *D*-9 of the American Society for Testing Materials. A series of reports was presented on a program of comparative measurements of glass in the high-frequency range. Other members presented brief informal reports on outstanding work in the general field of dielectrics. The technical meeting was held following a dinner tendered the Committee and its guests by Chairman Wheeler P. Davey.

Committee on Chemistry. The outstanding activity of this committee was the arrangement and conducting of a symposium on electrical insulating materials under joint auspices with the industrial and engineering division of the American Chemical Society, September 8, during the fall meeting of the Society in Milwaukee, Wis. (A report of this meeting was published in the October issue of Electrical Engineering, pages 426–7; an address by F. M. Clark (A'24) "A Chemical Approach to the Problem of High Voltage Dielectrics" which was presented at a dinner session of that meeting, may be found elsewhere in this issue.) Chairman F. L. Miller of the committee has other plans for further extending its usefulness.

Committee on Monographs. This committee has been very active in forwarding the production of a voluminous work on "The Electrochemistry of Dielectrics," by Glockler and Lind, originally planned as a monograph for the series published under the auspices of the conference. This work assumed such large proportions as to indicate the advisability of independent publication. Other monographs in view are "The Mapping of Electric Fields," by Ernst Weber (A'31, F'34), and "Solid Dielectrics" by S. O. Morgan and associates.

In accordance with his usual custom, Chairman Whitehead also included in his report a brief review of important contributions made during the past year to experimental research in the field of dielectrics and insulation; full text of that portion of his report is scheduled for publication in an early issue of Electrical Engineering.

In addition to the technical sessions, the meeting included also the annual dinner followed by an evening session during which an address "A Simple Derivation of the Maxwell-Boltzmann Law" was delivered by Doctor E. U. Condon of the Westinghouse research laboratories. The meeting schedule included also inspection trips to nearby points of interest. The 1939 meeting of the conference will be held at Harvard University, Cambridge, Mass., the date to be selected later.

Additional Curricula Accredited at Sixth Annual Meeting of ECPD

MARKING the culmination of five years of existence, the Engineers' Council for Professional Development held its sixth annual meeting in New York, N. Y., October 21–22, 1938. Included in the program were the election of officers and appointment of committees, presentation of annual reports by the chairman and committees, and a dinner meeting at which informal talks were given by ECPD officers and others.

A joint organization, ECPD is composed of representatives of the sponsoring societies, of which the AIEE is one; the others are the national societies of civil, mechanical, mining and metallurgical, and chemical engineers, the Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners. Its purpose is to enhance the professional status of the engineer. Its initial project has been the development of the young engineer, and this has been carried on through the efforts of four committees dealing with four stages in the evolution of the young engineer: student selection and guidance; engineering schools, professional training, and professional recognition.

A Continuing, Permanent Agency

In his annual report, Chairman C. F. Scott (A'92, F'25, HM'29) emphasized the idea of ECPD as a continuing, permanent agency. "In the first five years," he said, "we have been pioneering . . . in objectives, in co-operation, in scope, in method, and in results. Engineering groups have concerned themselves primarily with technological progress; through ECPD they now stress development of the individual engineer.... ECPD is...both exploratory and promotional. It proposes measures and, on approval, administers them primarily 'through the co-operative support' of the constituent organizations."

Speaking of the accomplishments of ECPD committees, Chairman Scott said: "Accrediting in engineering schools is acclaimed as the great achievement of ECPD." He characterized as a major problem the qualification of advisors, particularly high school staffs and local engineers, in the selection of the best qualified students for engineering courses. In answer to the question "After graduation—what?" Chairman Scott called attention to the great opportunity of the engineering societies to serve the profession by assisting the young engineer to continue his professional training after graduation looking toward the goal of "professional recognition."

"All this pioneering," Chairman Scott continued "proves that our projects are valuable, and continuing, and enlarging. In accrediting, our printed lists are not the end of the road, but the first milestone on a new highway. In a changing world, engineering must change, and our projects open a vision showing ways in which engineering can be made continuously better. If progressive engineering is basic to progressive civilization, our projects merit our full support through adequate organization and ample funds."

Major Committees Report

Most significant of the reports presented and acted upon at this meeting was that of the committee on engineering schools. In approving the report of this committee, which was presented by its chairman, Karl T. Compton (F'31), ECPD expanded its list of accredited engineering curricula to include a total of 472 courses in 112 educational institutions throughout the country. The complete list, together with an outline of the basis of accrediting, is given in the excerpts from the report of this committee appearing elsewhere in this issue.

After outlining the direction of effort of the committee on selection and guidance of engineering students, R. L. Sackett, chairman, briefly described the various ways in which the guidance problem is being attacked. He also reported on the extent of distribution of the booklet "Engineering: A Career—A Culture," reporting that about 18,000 copies had been sold since October 1937. Since only 25,000 copies remain in stock, he recommended that provision be made for early editorial review, publication, and more aggressive distribution of a revised and enlarged edition of this booklet. Chairman Sackett's report aroused considerable discussion, at the conclusion of which it was voted that an amount not to exceed $200 be allowed the committee for preparation of a manuscript for a revised booklet, to be submitted to ECPD for approval.

Following a restatement of the objective of the committee on professional training and a review of its past accomplishments, Chairman O. W. Eshbach of this committee presented a summary of committee activities during the year 1937–38. He reported that of the 2,000 copies of the pamphlet "Suggestions to Juniors and General Reading List" all but about 100 copies had been distributed; of the 2,000 copies of "Selected Bibliography of Engineering Subjects," between 500 and 700 copies of each of the various sections remain in stock; and approximately 1,000 copies of the pamphlet "University Extension Facilities," of the 2,000 printed, are still on hand. To clarify future plans of the committee, Chairman Eshbach reviewed the essential elements of professional development or training and briefly discussed problems that might be considered as fruitful fields of study. "There is a need to know more about the desires of youth, the influences which bring them into professional association, and the deficiencies in opportunity for them," he

New-Member Activity

Thanks to you who have already helped your Section membership chairman; others please send those names of prospective members at an early date.

National Membership Committee

List of Undergraduate Curricula of Educational Institutions Accredited by ECPD

(As of October 22, 1938, and subject to continual revision)

University of Alabama: Aeronautical, civil, electrical, industrial, mechanical, mining

University of Arizona: Civil, electrical, mechanical, mining

University of Arkansas: Civil, electrical, mechanical

Armour Institute of Technology: Chemical, civil, electrical, mechanical

Brooklyn Polytechnic Institute (*a*): Chemical, civil, electrical, mechanical

Brown University: Civil, electrical, mechanical

Bucknell University: Civil, electrical

University of California: Civil, electrical, mechanical, metallurgical (metallurgy), mining, petroleum

California Institute of Technology: Aeronautical (6-year course), chemical (5-year course), civil, electrical, mechanical

Carnegie Institute of Technology: Chemical, civil (*a*), electrical (*a*), industrial (management) (*a*), mechanical (*a*), metallurgical (*a*)

Case School of Applied Science: Chemical, civil, electrical, mechanical, metallurgical

Catholic University of America: Aeronautical, architectural, civil, electrical, mechanical

University of Cincinnati: Aeronautical, chemical, civil, electrical, mechanical

The Citadel: Civil

Clarkson College of Technology: Chemical, civil, electrical, mechanical

Clemson Agricultural College: Civil, electrical, mechanical

College of the City of New York (*a*): Civil, electrical, mechanical

University of Colorado: Architectural, civil, electrical, mechanical

Colorado School of Mines: Geological, metallurgical, mining, petroleum

Colorado State College: Civil, electrical, mechanical

Columbia University (*b*): Chemical, civil, electrical, industrial, mechanical, metallurgical, mining

Cooper Union Institute of Technology (*c*): Civil, electrical, mechanical

Cornell University: Chemical, civil, electrical, industrial (administrative), mechanical

Dartmouth College: Civil

University of Delaware: Civil, electrical, mechanical

University of Detroit: Aeronautical, architectural, civil, electrical, mechanical

Drexel Institute: Chemical, civil, electrical, mechanical

Duke University: Civil, electrical, mechanical

University of Florida: Civil, electrical, industrial, mechanical

Georgia School of Technology: Aeronautical, chemical (excluding co-operative curriculum), civil, electrical, mechanical

Harvard University (*e*): Civil, communication, electrical, industrial (engineering and business administration), mechanical, metallurgical (physical metallurgy), sanitary

Howard University: Civil, electrical, mechanical

University of Idaho: Civil, electrical, mechanical, metallurgical (metallurgy), mining

University of Illinois: Architectural, ceramic (technical option), chemical, civil, electrical, general (*e*), mechanical, metallurgical, mining

Iowa State College: Agricultural (*f*), architectural, chemical, civil, electrical, general (*e*), mechanical

State University of Iowa: Chemical, civil, electrical, mechanical

Johns Hopkins University: Civil, electrical, mechanical

University of Kansas: Architectural, civil, electrical, mechanical, mining

Kansas State College: Agricultural (*f*), architectural, civil, electrical, mechanical

University of Kentucky: Civil, metallurgical, mining

Lafayette College: Civil, electrical, industrial (administrative), mechanical, metallurgical, mining

Lehigh University: Chemical, civil, electrical, industrial, mechanical, metallurgical, mining

Louisiana State University: Civil, electrical, mechanical, petroleum

University of Louisville: Chemical, civil, electrical, mechanical

University of Maine: Civil, electrical, general (*e*), mechanical

Marquette University: Civil, electrical, mechanical

University of Maryland: Civil, electrical, mechanical

Massachusetts Institute of Technology: Aeronautical, building engineering and construction, chemical, civil, electrical, electrochemical, general (*e*), industrial (business and engineering administration), mechanical, metallurgical (metallurgy), mining naval architecture and marine engineering, public health, sanitary

University of Michigan: Aeronautical, chemical, civil, electrical, engineering mechanics, mechanical, metallurgical, naval architecture and marine engineering, transportation

Michigan College of Mining and Technology: Civil, electrical, mechanical, metallurgical, mining

Michigan State College: Civil, electrical, mechanical

University of Minnesota: Aeronautical, chemical, civil, electrical, mechanical, metallurgical, mining (excluding mining in geology option), petroleum

University of Missouri: Civil, electrical, mechanical

Missouri School of Mines and Metallurgy: Ceramic, civil, electrical, metallurgical, mining (mine) (excluding mining geology option)

Montana School of Mines: Geological, metallurgical, mining

Montana State College: Civil, electrical, mechanical

University of Nebraska: Agricultural (*f*), architectural, civil, electrical, mechanical

University of Nevada: Electrical, mechanical, mining

University of New Hampshire: Civil, electrical, mechanical

University of New Mexico: Civil, electrical, mechanical

New Mexico State College: Civil, electrical, mechanical

New York University: Aeronautical, chemical (*a*), civil (*a*), electrical (*a*), mechanical (*a*)

New York State College of Ceramics (at Alfred University): Ceramic

Newark College of Engineering: Civil, electrical, mechanical

North Carolina State College: Ceramic, civil, electrical, mechanical

University of North Dakota: Civil, electrical, mechanical, mining

Northwestern University: Civil, electrical, mechanical

Norwich University: Civil, electrical

Ohio State University: Ceramic, chemical, civil, electrical, industrial, mechanical, metallurgical, mining (mine)

University of Oklahoma: Architectural, civil, electrical, mechanical, petroleum (production option)

Oklahoma Agricultural and Mechanical College: Civil, electrical, industrial, mechanical

Oregon State College: Civil (excluding business option), electrical (excluding business option), mechanical (excluding business option)

University of Pennsylvania: Chemical, civil, electrical, mechanical

Pennsylvania State College: Architectural, ceramic (ceramics), chemical, civil, electrical, electrochemical, fuel technology, industrial, mechanical, metallurgical (metallurgy), mining, petroleum and natural gas, sanitary

University of Pittsburgh: Chemical, civil, electrical, industrial, mechanical, metallurgical, mining, petroleum

Princeton University: Chemical, civil, electrical, mechanical

Purdue University: Chemical, civil, electrical, mechanical

Rensselaer Polytechnic Institute: Aeronautical, chemical, civil, electrical, industrial, mechanical, metallurgical

Rhode Island State College: Civil, electrical, mechanical

Rice Institute: Civil, electrical, mechanical

University of Rochester: Mechanical

Rose Polytechnic Institute: Civil, electrical, mechanical

Rutgers University: Civil, electrical, mechanical, sanitary

University of Santa Clara: Civil, electrical, mechanical

South Dakota State College: Civil electrical, mechanical

South Dakota State School of Mines: Civil, electrical, metallurgical, mining

University of Southern California: Petroleum

Stanford University: Civil, electrical, mechanical, metallurgical, mining, petroleum

Stevens Institute of Technology (*e*): General

Swarthmore College: Civil, electrical, mechanical

Syracuse University: Civil, electrical, industrial (administrative), mechanical

University of Tennessee: Civil, electrical, mechanical

University of Texas: Architectural, civil, electrical, mechanical, petroleum (petroleum production)

Agricultural and Mechanical College of Texas: Civil, electrical, mechanical, petroleum

Texas Technological College: Civil electrical, mechanical

Tufts College: Civil, electrical, mechanical

Tulane University of Louisiana: Civil, electrical, mechanical

Union College: Civil, electrical

University of Utah: Civil, electrical, mechanical, metallurgical, mining

Utah State Agricultural College: Civil

University of Vermont: Electrical

University of Virginia: Civil, electrical, mechanical

Virginia Military Institute: Civil, electrical

Virginia Polytechnic Institute: Ceramic, chemical, civil, electrical, industrial, mechanical

Washington University: Architectural civil, electrical, industrial (administrative), mechanical

University of Washington: Aeronautical, ceramic, chemical, civil, electrical, mechanical, metallurgical, mining

State College of Washington: Architectural, civil, electrical (basic and hydroelectric, options), mechanical (basic option), metallurgical, mining (excluding mine administration and petroleum engineering option)

Webb Institute of Naval Architecture: Naval architecture and marine engineering

West Virginia University: Civil, electrical, mechanical, mining

University of Wisconsin: Chemical, civil, electrical, mechanical, metallurgical, mining

Worcester Polytechnic Institute: Civil, electrical, mechanical

Yale University: Chemical, civil, electrical, mechanical, metallurgical (metallurgy)

(*a*). Accrediting applies to both the day and evening curricula.

(*b*). Accrediting applies to the 4-year and 5-year curricula leading to the bachelor of science degree.

(*c*). Accrediting applies to day curriculum only. Action on evening curriculum deferred pending granting of degrees.

(*d*). Accrediting applies only to curriculum as submitted to ECPD and upon completion of which a certificate is issued by Harvard University certifying that the student has pursued such a curriculum.

(*e*). The accrediting of a curriculum in general engineering implies satisfactory training in engineering sciences and in the basic subjects pertaining to several fields of engineering; it does not imply the accrediting, as separate curricula, of those component portions of the curriculum such as civil, mechanical, or electrical engineering that are usually offered as complete professional curricula leading to degrees in these particular fields.

(*f*). All accredited curricula in agricultural engineering have been provisionally accredited for a period of two years. The reason for this is twofold: First it appears to ECPD that the final year of the four-year program fails to build adequately upon the engineering basis laid in the first three years; secondly, it seems to ECPD that such curricula might better be given as options under one of the major engineering branches (i. e., civil, electrical, or mechanical engineering).

said. "At the same time, however, it is important to bring about unity in thinking on the part of those locally responsible for professional activities. Opinion should crystallize or grow out of experience with practical field situations. The committee, therefore, recommends that before it undertakes any further major activities a joint study be made, through the educational committees and Section chairmen of the several societies. This investigation should ascertain: (1) the nature of present activities, (2) the facilities available for them, (3) the manner in which they are sponsored and promoted, (4) the response to them. The report should attempt to crystallize opinion as to: (1) further policy (2) fields of activity of the several educational committees (3) means of co-ordination with local educational institutions and, if necessary, between societies (4) more effective ways of increasing membership." As future studies that might be undertaken if the required financial support could be obtained, Mr. Eshbach cited graduate study, opportunities for engineers, culture, co-operative education, and self-education.

A progress report of the committee on professional recognition was presented by J. W. Barker (M'26, F'30) member of this committee. He first reported what had been accomplished toward revision of the "Model Law for the Registration of Professional Engineers and Land Surveyors." He explained that the committee was concerned with uniformity in engineers registration laws, and not with the philosophy of registration. A voluminous collection of information concerning the methods of professional recognition used in other professions is being duplicated so that the committee can study it with a view toward later report and recommendation.

ECPD Officers Elected and Committees Appointed

As its chairman for the ensuing year, ECPD elected J. P. H. Perry, vice-president, Turner Construction Company, New York, N. Y. For vice-chairman, R. E. Doherty (A'16, M'27) president, Carnegie Institute of Technology, Pittsburgh, Pa., was named. S. L. Tyler, secretary, American Institute of Chemical Engineers, New York, N. Y., was elected secretary of ECPD; and C. E. Davies, secretary, The American Society of Mechanical Engineers, New York, N. Y., was re-elected assistant secretary. Chairmen of three committees were reappointed as follows: R. L. Sackett, student selection and guidance; Karl T. Compton (F'31) engineering schools; and O. W. Eshbach (A'17, F'37) professional training. C. F. Scott, retiring ECPD chairman, was appointed chairman of the committee on professional recognition.

Upon recommendation of the retiring executive committee, the following were reappointed to the executive committee for the ensuing year: C. F. Hirshfeld (A'05, F'36) representing The American Society of Mechanical Engineers [A. R. Stevenson, Jr. (A'20, F'37) alternate]; L. W. W. Morrow (A'13, F'25) representing the AIEE; H. C. Parmelee, representing the American Institute of Chemical Engineers; and D. B. Steinman, representing the National Council of State Boards of Engineering Examiners. Members newly elected to the executive committee were: E. R. Needles, representing the American Society of Civil Engineers; G. B. Waterhouse, representing the American Institute of Mining and Metallurgical Engineers; and R. E. Doherty (A'16, M'27) representing the Society for the Promotion of Engineering Education (Doctor Doherty was an alternate during 1937–38).

Appointments of the following representatives by the various societies for the three-year term 1938–41 were announced: ASCE, E. R. Needles (reappointment); AIME, G. B. Waterhouse (reappointment); ASME, H. T. Woolson; AIEE, J. F. Fairman (A'20, F'35); AIChE, W. N. Jones (reappointment); SPEE, C. C. Williams; and NCSBEE, N. W. Dougherty.

Report of ECPD Committee on Engineering Schools

In presenting the report of the ECPD committee on engineering schools, Chairman Karl T. Compton (F'31) restated the general objective of the committee and briefly reviewed the accomplishments of previous years. He said that at the end of 1937 (*EE Nov. '37, p. 1418*) 626 curricula at 129 institutions had been inspected, and final action taken on 617 curricula. Concerning activities during the current year, Chairman Compton said that "further material progress can be reported." He submitted recommendations on 62 additional curricula involving 6 institutions submitting curricula for the first time. Among those reinspected were 22 curricula previously accorded term accrediting, and 7 curricula initially not accredited. Including the additional curricula formally accredited by approval of this report, the current list includes 472 accredited undergraduate curricula at 112 institutions (see accompanying tabulation).

Basis for Accrediting Engineering Colleges

The following statement, proposed by the committee on engineering schools and approved by ECPD and by the constituent member organizations, embodies the principles in accordance with which accrediting is conducted.

I. Purpose of accrediting shall be to identify those institutions which offer professional curricula in engineering worthy of recognition as such.

II. Accrediting shall apply only to those curricula which lead to degrees.

III. Both undergraduate and graduate curricula shall be accredited. (Accrediting program at present embraces undergraduate curricula only.)

IV. Curricula in each institution shall be accredited individually. For this purpose, the ECPD will recognize the six major curricula: chemical, civil, electrical, mechanical, metallurgical, and mining engineering—represented in its own organization, and such other curricula as are warranted by the educational and industrial conditions pertaining to them.

V. Curricula shall be accredited on the basis of both qualitative and quantitative criteria.

VI. Qualitative criteria shall be evaluated through visits of inspection by a committee or committees of qualified individuals representing the ECPD.

VII. Quantitative criteria shall be evaluated through data secured from catalogs and other publications, and from questionnaires.

VIII. Qualitative criteria shall include the following:

1. Qualifications, experience, intellectual interests, attainments, and professional productivity of members of the faculty.
2. Standards and quality of instruction: (*a*) in the engineering departments; (*b*) in the scientific and other co-operating departments in which engineering students receive instruction.
3. Scholastic work of students.
4. Records of graduates both in graduate study and in practice.
5. Attitude and policy of administration toward its engineering division and toward teaching, research, and scholarly production.

IX. Quantitative criteria shall include the following:

1. Auspices, control, and organization of the institution and of the engineering division.
2. Curricula offered and degrees conferred.
3. Age of the institution and of the individual curricula.
4. Basis of and requirements for admission of students.
5. Number of students enrolled: (*a*) in the engineering college or division as a whole; (*b*) in the individual curricula.
6. Graduation requirements.
7. Teaching staff and teaching loads.
8. Physical facilities—the educational plant devoted to engineering education.
9. Finances: Investments, expenditures, sources of income.

Information supplied by means of the questionnaire, or otherwise, is for the confidential use of the ECPD and its agents and will not be disclosed without the specific written authorization of the institution concerned.

Commenting further on current progress, Chairman Compton said: "An important activity of the committee during the year has been the giving of advisory service to institutions which have had curricula not accredited, or at which curricula have been accredited for a limited term. In the case of seven curricula, the advisory service culminated in formal reconsideration. In other cases, although many suggested improvements have been made, the institutions are still unprepared to submit curricula for reinspection.

"During the year the committee has focused attention on plans for assuring the continuation of the accrediting program... Encouraging progress was made both in the direction of evolving a suitable plan for reinspection and review, and in the direction also of obtaining assurance of support from institutions."

Chairman Compton then outlined the extent of tasks remaining for the committee, and discussed some of the problems involved in accrediting. Concerning the standards of accrediting, he said: "It has been noted that the committee has adhered rigidly to the policy that it should set no fixed standards for use as yardsticks in measuring the quality of engineering instruction. On the contrary, institutions and curricula are judged on broad, general grounds, rather than on details, and each institution is appraised in the light of local conditions. The committee strongly believes that there should be no rigid 'norm' for engineering education, and that institutions should be accorded wide latitude to decide for themselves upon educational policies.

"One principle is insisted upon, however, namely, that if any curriculum omits some portion of a subject in which engineers in that field are expected by the public to have competence, under such conditions the committee considers it a necessary safeguard to the public that the curriculum be not accredited.

"A direct source of gratification is the way in which institutions have been able to benefit from accrediting. Almost without exception the committees of inspection have been asked for suggestions and advice. A sincere effort has been made to meet these requests, and each committee of inspection conscientiously endeavors to notice ways along which efforts toward improvement might advantageously be directed. The appreciative comments and letters received, and the way in which suggestions have been acted upon speak for the success attained, in spite of some failures to do all that might have been done had time been adequate and human performance perfect. In addition, many institutions are using the list as a basis for admission to the engineering school of students transferring from other institutions.

"Another valuable feature of ECPD accrediting is the way in which it has eliminated multiplicity of accrediting in the field of engineering education. Several agencies not formally connected with ECPD have gratefully accepted the accredited list and during the past year notable success of the accrediting program was evidence in the unreserved endorsement of the list by the National Council of State Boards of Engineering Examiners. Thus one of the major objectives of the program has been met."

Chairman Compton concluded his report with an outline of major future activities for the committee and a summary of the committee's finances.

National Defense Power Committee Announces Standards for Turbine Generators

According to an official release from the War Department, the National Defense Power Committee approved November 14 the report of its subcommittee on standardization establishing, for the first time in the history of the electrical industry, preferred standards for steam turbine-generators of 10,000 kilowatts rating and above with a view to expediting the production and reducing the costs of such equipment. The adoption of these standards is expected materially to accelerate the construction and erection of generating stations to provide additional supplies of electric energy. The committee is considering similar determinations for generators of smaller ratings.

Definite standards of pressure, temperature, voltage, power factor, and other technical features, are provided for nine sizes of condensing turbines, ranging from 10,000 to 100,000 kilowatts and for eight sizes of superposed turbines ranging from 10,000 to 60,000 kilowatts. In the past, turbines and generators of these large capacities have been chiefly "tailor-made jobs" built to order on special designs prepared by utility engineers. This has meant the expenditure of a large amount of time on engineering and design for each machine and in large part has prevented the adoption of quantity methods of production.

The subcommittee on standardization, of which Commissioner Basil Manly of the Federal Power Commission is chairman, while establishing these preferred standards, states that it "has been careful in its report to provide sufficient latitude for the modification of the standards to meet the special conditions arising in connection with the installation of new equipment in existing plants or where unusual physical conditions must be met. Provision also is made for the consideration of technical advances in the art. But in every case where deviation from the preferred standards is suggested, the burden of proof will be upon the utility or manufacturer proposing such deviation. The committee states that at all times it will welcome constructive suggestions from the industry.

These provisions are emphasized in the technical report prepared for the subcommittee by Dr. John C. Parker, president of the American Institute of Electrical Engineers and vice-president of the Consolidated Edison Company, representing the utilities;

Table I. Condensing Turbines

1	Rating (kw)	10,000	12,500	15,000	20,000	25,000	35,000	50,000	75,000	100,000
2	Revolutions per min	3,600	3,600	3,600	3,600	3,600	3,600	3,600	1,800	1,800
3	Throttle pressure (pounds per sq in. gauge)	650	650	650	850	850	850 or 1,250	850 or 1,250	850 or 1,250	850 or 1,250
4	Throttle temp. (deg F)	825	825	825	900	900	900	900	900	900
5	Number of extraction openings	3	3	3	3	3	4	4	4	4
6	Temp. at extraction openings ± 10 deg F (at rated output)	170/225/ 290	170/225/ 290	170/225/ 290	170/225/ 290	170/225/ 290	170/225/ 290/350	170/225/ 290/350	170/225/ 290/350	170/225/ 290/350
7	Turbine capacity in % of kw rating	125	125	125	125	125	125	125	125	125
8	Power factor	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
9	Generator cooling	Air	Air	Air	Air	Air or hydrogen	Hydrogen	Hydrogen	Hydrogen	Hydrogen

General: All sizes—back pressure 1 inch or 1½ inch mercury absolute; short-circuit ratio 0.9; generator voltage 13,800*; excitation voltage 250.
* 11, 11.5, 12, 13.2, or 14.4 kv may be furnished if required to meet the needs of an existing system.

Table II. Superposed Turbines

10	Rating (kw)	10,000	12,500	15,000	20,000	25,000	35,000	50,000	60,000
11	Turbine capacity in % of kw rating	111	111	111	111	111	111	111	111
12	Power factor	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8 or 0.9
13	Generator cooling	Air	Air	Air	Air	Air or hydrogen	Hydrogen	Hydrogen	Hydrogen

General: All sizes—3,600 rpm; throttle pressure and temperature 1,250 pounds per square inch gauge, 925 degrees fahrenheit; back pressure 200–300 pounds per square inch gauge; short-circuit ratio 0.9; generator voltage 13,800*; excitation voltage 250.
* 11, 11.5, 12, 13.2, or 14.4 kv may be furnished if required to meet the needs of an existing system.

Future Meetings of Other Societies

American Association for the Advancement of Science. Winter meeting, December 27–31, Richmond, Va.

American Institute of Mining and Metallurgical Engineers. Annual meeting, February 13–16, 1939, New York, N. Y.

American Physical Society. 224th meeting, December, Los Angeles, Calif.

40th annual meeting, December 27–29, Washington, D. C.

American Society of Civil Engineers. Annual meeting, January 18–20, New York, N. Y.

American Society of Heating and Ventilating Engineers. 1939 annual meeting, January 23–26, Pittsburgh, Pa.

American Society of Mechanical Engineers. Spring meeting, February 23–25, 1939, New Orleans, La.

Machine and tool progress exhibition. March 14–18, 1939, Detroit, Mich.

American Society of Testing Materials. Committee week, March 6–10, 1939, Columbus, Ohio

1939 annual meeting, June 26–30, Atlantic City, N. J.

National Electrical Manufacturers Association. Midwinter conference, February 5–11, 1939, New York, N. Y.

Society of Automotive Engineers. Annual meeting, January 9–13, 1939, Detroit, Mich.

C. S. Coggeshall, sales manager, turbine department of the General Electric Company, representing the electrical equipment manufacturers, and Thomas R. Tate, representing the National Defense Power Committee. This report states:

"Your subcommittee on standardization of turbine-generators has held two meetings, one on October 20, and another on November 3, at which representatives of the turbine generator manufacturers, utilities and the Government were present and co-operated wholeheartedly in discussing the adoption of preferred standards for steam turbine generators of 10,000 kilowatts rating and above. The subcommittee has unanimously agreed upon and recommends for adoption by industry and the manufacturers the standards set forth herein.

"The immediate objective of the establishment of preferred standards for turbine generators is the maximum speed of provision of power facilities to anticipate peacetime requirements and to facilitate wartime provision of power through elimination of any unnecessary special designs or sizes. It is expected, incidentally, that the cost of power plant installations will be reduced sufficiently to compensate for any added economy or other advantages that might result from more special designs.

"It is the belief of your subcommittee that the advantages of preferred standards as here recommended for turbine-generators will be reflected also in such associated equipment as boilers and appurtenances, steam piping, valves, and fittings.

"It is the intention that the preferred standards agreed upon by representatives of the Government, the manufacturers, and the utilities, will be followed in the building of all new generating stations and in all installations within existing stations unless interrelation with existing equipment clearly calls for special designs. Deviation from these proposed standards, if of decided advantage to the public, or if necessitated by physical conditions, or by the fundamental purpose of rapid creation of power facilities for national defense, will be deemed to be consistent with this program. In all such cases the burden of clear proof rests upon any one proposing such deviation.

"Illustrative of such cases in which deviation will be deemed to be in the spirit of this program—but not intended to be all inclusive—are the following:

(1) The temperature of condensing water supply may require turbines designed for operation with back-pressures higher than herein provided.

(2) The present availability in manufacturers' plants of turbine-generators well advanced in production points clearly to the completion and use of such equipment.

(3) Duplication of a turbine-generator, not currently discontinued by the manufacturer as an active design, may expedite manufacture and installation of power facilities.

(4) The manufacture and installation of turbine-generators adapted to meet essential requirements in existing stations may facilitate rapid creation of generating capacity.

"The preferred standards are intended to be progressive standards and, consistently with the fundamental purpose of expediting production and installation of power-generating equipment, are intended to permit technical and economic developments. To that end they should, at least annually, and as occasion seems clearly to warrant, be reviewed to determine whether advances in the art call for specific modification."

Those participating in the conferences which resulted in the recommendations of preferred standards were:

1. For the National Defense Power Committee—Assistant Secretary of War Louis Johnson; Federal Power Commissioner Basil Manly; Captain William R. Winslow; Mr. Thomas R. Tate; Lieutenant-Colonel L. E. Atkins and Mr. Carl H. Giroux, U. S. Army; Commander K. B. Bragg, U. S. Navy.

2. For the electrical equipment manufacturers: Allis-Chalmers Manufacturing Company—A. C. Flory, manager, steam turbine department; R. N. Landreth. General Electric Company—C. S. Coggeshall; A. F. E. Horn; A. R. Smith, manager, steam turbine department; A. O. White. Westinghouse Electric and Manufacturing Company—C. A. Bercaw; C. B. Campbell, manager, turbine department; G. H. Cox; Ralph Kelly; C. F. Lloyd; R. A. McCarty.

3. For the electric utilities: K. M. Irwin, vice-president in charge of engineering, Philadelphia Electric Company; H. B. Gear, vice-president, Commonwealth Edison Company of Chicago; Dr. John C. Parker, vice-president, Consolidated Edison Company of New York, Inc.

The accompanying tables show the preferred standards for steam turbine-generators adopted by the National Power Defense Committee's subcommittee on standardization.

United Engineering Trustees, Inc.

The Joint Engineering Organizations

United Engineering Trustees, Inc., one of the joint agencies supported and participated in by the AIEE, was organized in 1904 as an instrumentality of the Founder Societies, the four national societies of civil, mining and metallurgical, mechanical, and electrical engineers. Its purpose is the managing of property and funds in which these societies have joint interests, and it is governed by trustees duly appointed by the societies as their representatives. It maintains two departments: (1) the Engineering Societies Library, and (2) The Engineering Foundation.

The corporation (UET, Inc.) manages the Engineering Societies Building and all trust funds placed in the hands of UET, Inc.

The Engineering Societies Library is a free public engineering library, which is operated for users at a distance, as well as for those who visit its rooms in the Engineering Societies Building.

The Engineering Foundation, founded by the late Ambrose Swasey in 1914, is entrusted with the expenditure of income from endowment and other funds. The ultimate objective of Foundation is stated to be: "for the furtherance of research in science and engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind."

In the accompanying articles may be found announcements of the elections recently held by UET and The Engineering Foundation, and abstracts of the annual reports of these organizations and of the Engineering Societies Library.

Election of Officers of United Engineering Trustees, Inc.

Officers to serve the United Engineering Trustees, Inc., for the year 1938–39 were elected at the recent annual meeting of UET. D. Robert Yarnall, chief engineer of the Yarnall-Waring Company, Philadelphia, Pa., was re-elected president, and H. A. Lardner (A'94, F'13) and Albert Roberts were re-elected vice-presidents. Other officers re-elected were H. R. Woodrow (A'12, F'23) treasurer; J. P. H. Perry, assistant treasurer; and John H. R. Arms, secretary and general manager; the first five comprise the executive committee.

Members of the board of trustees of UET for the year 1938–39, including both new and hold-over members, are:

Terms expiring October 1939

J. P. Hogan	ASCE representative
Albert Roberts	AIME representative
D. Robert Yarnall	ASME representative
H. P. Charlesworth (M'22, F'28, past-president)	AIEE representative

Terms expiring October 1940

Otis E. Hovey	ASCE representative
W. D. B. Motter, Jr.	AIME representative
Kenneth H. Condit	ASME representative
H. R. Woodrow (A'12, F'23)	AIEE representative

Terms expiring October 1941

A. L. J. Queneau	AIME representative
F. M. Farmer (A'02, F'13, vice-president)	AIEE representative

Terms expiring October 1942

J. P. H. Perry	ASCE representative
Henry A. Lardner	ASME representative

Of these, J. P. H. Perry and Henry A. Lardner were reappointed; all others are held over. The following committees were reappointed:

Finance: Albert Roberts, chairman; J. P. Hogan, H. A. Lardner, H. R. Woodrow, D. Robert Yarnall, ex-officio.

Real Estate: J. P. H. Perry, chairman, A. L. J. Queneau, Kenneth H. Condit, H. P. Charlesworth, D. Robert Yarnall, ex-officio.

The personnel of other committees as appointed or reappointed at this meeting is as follows:

IRON ALLOYS

G. B. Waterhouse, *chairman*, professor of metallurgy, Massachusetts Institute of Technology, Cambridge, Mass., representing AIME.

Lyman J. Briggs, director, National Bureau of Standards, represented by J. G. Thompson, chief of section on chemical metallurgy, National Bureau of Standards, Washington, D. C.

J. W. Finch, director, United States Bureau of Mines, represented by R. S. Dean, chief engineer, Metallurgical Division, Washington, D. C.

J. T. MacKenzie, metallurgist and chief chemist, American Cast Iron Pipe Company, Birmingham, Ala., representing American Foundrymen's Association.

John Johnston, director of research, United States Steel Corporation, Kearny, N. J., representing American Iron and Steel Institute.

Bradley Stoughton, dean of engineering, Lehigh University, Bethlehem, Pa., representing American Society for Metals.

Jerome Strauss, vice-president, Vanadium Corporation of America, Bridgeville, Pa., representing American Society for Testing Materials.

T. H. Wickenden, metallurgical engineer, International Nickel Company, New York, N. Y., representing The Society of Automotive Engineers.

Engineering Foundation Elects Officers

At the recent annual meeting of The Engineering Foundation, F. M. Farmer (A'02, F'13, vice-president) was re-elected chairman for the year 1938–39, and George E. Beggs was elected vice-chairman. These two, together with A. L. J. Queneau, W. I. Slichter (A'00, F'12, national treasurer), and K. H. Condit, comprise the executive committee.

Other re-elections were O. E. Hovey, director, and John H. R. Arms, secretary.

These officers and the executive committee of The Engineering Foundation are elected by the Foundation board, from among its own members. The board is itself elected by the board of trustees of United Engineering Trustees, Inc. The complete membership of the Engineering Foundation board for the year 1938–39 is:

Name		Term Expires
Four Trustees of UET, Inc.		
A. L. J. Queneau	AIME	1941
K. H. Condit	ASME	1939
H. P. Charlesworth	AIEE	1939
O. E. Hovey	ASCE	1941
Eight Members Nominated by Founder Societies		
George D. Barron	AIME	1940
George E. Beggs	ASCE	1939
F. F. Colcord	AIME	1942
F. M. Farmer	AIEE	1939
W. H. Fulweiler	ASME	1940
E. M. T. Ryder	ASCE	1942
W. I. Slichter	AIEE	1940
Albert E. White	ASME	1939
Three Members-at-Large		
O. E. Buckley	AIEE	1942
John V. N. Dorr	AIME	1939
Edwards R. Fish	ASME	1939
Ex-officio, President UET, Inc.		
D. Robert Yarnall	ASME	

Members of the research procedure committee as appointed or reappointed are:

F. F. Colcord, chairman, representing The Engineering Foundation.

K. H. Condit, representing The Engineering Foundation.

L. W. Chubb (A'09, F'21, past director) director, research laboratories, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., representing AIEE.

W. H. Fulweiler, Philadelphia, Pa., representing ASME.

Sam Tour, Lucius Pitkin, Inc., New York, N. Y., representing AIME.

H. E. Wessman, New York University, New York, N. Y., representing ASCE.

F. M. Farmer, ex-officio.

Table I. Summary of Annual Report of Finance Committee of UET, Inc.

Operation of Building

Operating revenue	$ 163,020.71
Less operating expenditures	157,834.49
Gross operating credit	5,186.22
Transferred to general reserve fund	1,500.00
Operating gain 1937–38	3,686.22
Operating credit from previous years	9,496.92
	13,183.14
Less accounts written off	145.00
Net balance September 30, 1938	$ 13,038.14

Operation of Library

Maintenance revenue	$ 46,707.84	
Maintenance expenditures	47,214.28	
Debit balance for year 1938	506.44	
Credit balance for previous year	6,578.67	
Credit balance September 30, 1938		$ 6,072.23
Service Bureau revenue	8,340.00	
Service Bureau expenditures and adjustments	7,978.18	
Credit balance for year 1938	361.82	
Credit balance from previous year	5,861.74	
Credit balance September 30, 1938		6,223.59
Total net operating credit balance cumulated to September 30, 1938		$ 12,295.79

Funds and Property

*** Combined Fund: Summary of Investments, September 30, 1938**

	Legal	Nonlegal	Book Value	Market Value
Funds included:				
Engineering Foundation fund	$491,710.60	$283,224.88	$ 774,935.48	
Edward Dean Adams fund		90,872.61	90,872.61	
Library endowment fund	92,240.18	75,209.90	167,450.08	
Depreciation and renewal fund		384,055.44	384,055.44	
General reserve fund		10,189.62	10,189.62	
Total	$583,950.78	$843,552.45	$1,427,503.23	
Investments: Legal			$ 346,422.00	
Nonlegal			1,075,702.89	
Total investment, September 30, 1938			1,422,124.89	$1,214,482.08
Cash uninvested			5,378.34	
			$1,427,503.23	
Real estate, cost of—September 30, 1938			$1,993,793.92	
Operating cash			24,770.37	
Accounts receivable, gross			1,558.95	
The Engineering Foundation—unexpended income			29,873.42	
Alloys of iron research—unexpended income			5,594.75	
The Engineering Foundation custodian fund assets			3,051.23	
Welding research—unexpended income			1,215.32	
Henry R. Towne engineering fund			50,349.36	$ 27,700.16
Fifth Swasey gift			86,977.16	$ 86,436.69
Total			$3,624,687.71	

Moneys Held for Special Purposes

Endowment committee (Adams expense fund)	$ 702.57

UET, Inc., Custodian of John Fritz Medal Fund

Securities held September 30, 1938	$ 3,500.00	$ 3,517.50
Cash on hand September 30, 1938	277.23	

* A group of funds managed as one for convenience and economy in investment transactions.

J. H. Critchett, vice-president, Union Carbide and Carbon Research Laboratories, Inc., New York, N. Y., representing American Electrochemical Society.

Wilfred Sykes (A'09, F'14, past manager) assistant to the president, Inland Steel Company, Chicago, Ill.; member-at-large.

F. T. Sisco, *editor*.

WELDING RESEARCH

C. A. Adams (A'94, F'13, past-president) *chairman;* consulting engineer, Edward G. Budd Manufacturing Company, Philadelphia, Pa.

H. C. Boardman, research engineer, Chicago Bridge and Iron Company, Chicago, Ill.

Everett Chapman, president, Lukenweld, Inc., Coatesville, Pa.

J. H. Critchett, vice-president, Union Carbide and Carbon Research Laboratories, Inc., New York, N. Y.

J. J. Crowe, engineer-in-charge of apparatus, research, and development department of Air Reduction Company, Jersey City, N. J.

A. S. Douglass, construction engineer, Detroit Edison Company, Detroit, Mich.

C. L. Eksergian, chief engineer, Budd Wheel Company, Detroit, Mich.

A. J. Ely, mechanical engineer, Standard Oil Development Company, Elizabeth, N. J.

H. M. Hobart (A'94, F'12, past vice-president) consulting engineer, General Electric Company, Schenectady, N. Y.

D. S. Jacobus (A'03) advisory engineer, The Babcock and Wilcox Company, New York, N. Y.

G. F. Jenks, colonel, Ordnance Department, United States Army, Washington, D. C.

Jonathan Jones, chief engineer, fabricated steel construction, Bethlehem Steel Company, Bethlehem, Pa.

P. G. Lang, Jr., engineer of bridges, Baltimore and Ohio Railroad, Baltimore, Md.

F. T. Llewellyn, research engineer, United States Steel Corporation, New York, N. Y.

Aubrey Weymouth, vice-president and chief engineer, Post and McCord, Inc., New York, N. Y. (Alternate for Jonathan Jones.)

William Spraragen (A'17, M'26) *secretary*, technical secretary and editor, New York, N. Y.

Chairman Farmer was reappointed Foundation's representative on the executive board of National Research Council, and O. E. Hovey was appointed representative on the highway research board.

Annual Report Issued by United Engineering Trustees, Inc.

The annual report of United Engineering Trustees, Inc., for the year ending September 30, 1938, has been submitted to the AIEE and other participating societies by D. Robert Yarnall, president. The report reveals continued financial stability as a whole, practically full occupancy of the Engineering Societies Building, gratifying use of meeting halls, and greater protection of the building. The physical condition of the building has been maintained and during the year extensive deferred mechanical maintenance has been met. The property remains on the tax-exempt rolls. Gratuitous use of meeting rooms has been granted to federal, state, and municipal organizations for military and WPA projects, and in co-operation with WPA and the board of education of the City of New York, to adult education classes in mathematics, languages, and other popular subjects.

During the year, Ambrose Swasey's fifth gift was written onto the books at $86,977.16, bringing his gifts to a total book value of $818,632.91. The depreciation and renewal fund was brought to a total of $384,055.44 against a 32-year-old building carried at $1,453,793.92. The capital investment in the property has been increased $6,000 by the addition of library shelving for use of Engineering Societies Library, paid by assessment against the Founder Societies. This addition is expected to provide storage for library acquisitions for the coming five years. A summary of the report of the UET finance committee is given in table I.

Annual Report Issued by Engineering Societies Library

The annual report of the Engineering Societies Library, containing information on the use of the library, its finances, and acquisitions, for the year ending September 30, 1938, has been submitted to the AIEE and other participating societies by Harrison W. Craver, director.

The number of readers was 31,376, an increase of 4,626 over 1936–37. In addition the library aided 10,574 other persons in various ways: 121 by lending 141 books; 78 by making searches and copies; 113 by making translations; 2,590 by making 20,869 photoprints; 2,974 by letter; and 4,698 by telephone. By these various ways, the library was used by 41,950 persons, 4,973 more than in the previous year. Requests for assistance have covered a wide variety of subjects and have come from every part of the earth.

On October 1, 1937 the library contained 141,292 volumes, 7,330 maps, and 4,362 manuscript bibliographies. Additions during the year were 3,091 volumes, 118 maps, and 29 bibliographies. One hundred twenty-one volumes and 40 maps were withdrawn, making the stock at end of the year 144,262 volumes, 7,408 maps, and 4,391 manuscript bibliographies. In addition, 3,248 pamphlets were added to volumes already counted. The lending collection contained 703 volumes and the number of duplicates is approximately 12,000 volumes.

In addition to cataloging current accessions as received, work has been carried on throughout the year in recataloging the pamphlets in the Wheeler collection, to conform with the system now in use. With the exception of a collection of Russian pamphlets and one of trade catalogs, and a few recent gifts, all material is cataloged and available for use.

Through the continuation of a gift of W. S. Barstow (A'94, F'12), work has continued during the year on repairing and rebinding valuable old books.

The periodical index now contains over 225,000 references to important engineering articles, classified by the universal decimal system, of which 21,000 were added during the current year.

During the year 4,146 volumes, 9,748 pamphlets, 118 maps, and 29 bibliographies were acquired by purchase or gift, a total of 14,041 items. Of these 3,091 volumes, 3,248 pamphlets, 118 maps, and 29 bibliographies were added to the permanent collection, a total of 6,486 additions. Thirty-five other volumes were placed in the loan collection. The remaining items of possible usefulness were added to the duplicate collection, to be sold or exchanged as opportunity occurs; the residue was discarded as waste paper. Sales of duplicates amounted to $407.47.

The number of periodicals received currently was 1,369. Six hundred twenty-nine volumes, worth approximately $2,200 were received for review.

The gifts numbered 12,242 items. Among the donors were the American Institute of Chemical Engineers, Professor George E. Case, the Bridgeport Public Library, the *Engineering News-Record*, E. R. Fish, Miss B. Haupt, Mrs. William B. Jackson, M. Kammerhoff, the New York Bar Association, George A. Orrok, Port of New York Authority, Shepherd F. Smith, and Arthur F. Tuttle.

At the request of the officers of the Engineering Institute of Canada, arrangements were made to supply the *Engineering Journal*, the organ of the Institute, with notices of new books.

Physical improvements of considerable magnitude have been made. A special appropriation by the Founder Societies made possible the erection of additional shelving, which has relieved overcrowding.

The budget for general operations was $48,100. Of this $35,959.70 was appropriated by the Founder Societies as follows:

American Society of Civil Engineers	$9,631.40
American Institute of Mining and Metallurgical Engineers	7,520.90
American Society of Mechanical Engineers	9,118.10
American Institute of Electrical Engineers	9,689.30

Expenditures from this budget amounted to $47,214.28 of which $9,534.18 was spent for books and other equipment of permanent value. The service bureau received $8,340.00 and spent $7,942.04.

Annual Report Issued by Engineering Foundation

The annual report of The Engineering Foundation for the year ending September 30, 1938, has been submitted to the AIEE and other participating societies by F. M. Farmer (A'02, F'13, vice-president) chairman of the Foundation board, who was assisted by Otis E. Hovey, director.

A summary of the capital fund of The Engineering Foundation and a condensed financial statement follow:

Capital Funds

Endowment, total book value on September 30, 1938	$871,000.00
E. H. McHenry bequest in hands of executors until decease of two life beneficiaries, appraised at probate of will in 1931, approximately	$400,000.00
Fifth Swasey gift	$ 86,977.16

The capital funds are held and administered by United Engineering Trustees, Inc. The net income from endowment was $42,516.69 for the fiscal year ended September 30, 1938. The Foundation board has discretion in use of income. For many of the enterprises which the Foundation has aided, large contributions of money, services, and materials have been obtained from others.

Expendable Resources—Summary

Balance on October 1, 1937		$ 24,555.11
Receipts		
Income from endowment	$42,516.69	
Income from minor items	1,362.27	43,878.96
Total resources		$ 68,434.07

Disbursements—Summary

Research projects	$30,161.38	
Promotion of research and administrative expenses	8,399.27	
Total for furtherance and support of research		38,560.65
Balance on October 1, 1938		$ 29,873.42

Money "contributions" from organizations and individuals, for specific activities, passed through the Foundation's accounts from its organization to September 30, 1938, totaled $316,703.81.

During the report year, in order to carry out the purposes of the Foundation, a total of 72 projects dealing with engineering and technical research, and the broader nontechnical matters of concern to the engineering profession had been or were being assisted by money grants. Work on 20 active projects, in 2 of which the AIEE is interested directly, has progressed during the year. In order to establish personal contacts and closer co-operation with those in charge of technical researches which are being supported or assisted by grants from the Foundation, the director has visited during the year most of the institutions and laboratories at which these researches are being conducted. A summary of activities follows:

Soil Mechanics and Foundations Division (ASCE). The following studies are included:

Earths, Dams, and Embankments ($500). Five subcommittees have been assigned to specific phases of the problem. The principal activity has been collecting data and ideas on the methods used for determining settlement in earth fills during and after construction, and for determining internal pressures in earth fills.

Sampling and Testing ($2,500). The work of the committee mainly has been studies for better methods of obtaining undisturbed samples and of the causes and effects of distortion and swelling of such samples. The work is being done with the co-operation of several laboratories, and interested companies.

Seepage and Erosion ($750). The project consisting of model investigations of seepage phenomena in earth dams has been continued at the University of Minnesota. A report is expected within the next few months.

Foundations ($1,500). Investigations have continued of structures in Europe. Data have been collected on settlements of structures in Egypt and papers on this and data on lateral earth and concrete pressures are to be presented.

Special Committee on Hydraulic Research (ASCE). The following studies are included:

Conversion of Kinetic to Potential Energy in Expanding Conduits ($300). The tests of a transparent conical expansion $7^1/_2$ inches long connecting transparent pipes 3 inches and 5 inches in diameter, have been completed, and the tests of sudden expansion are nearly finished. A mass of photographic and statistical data has been collected and is being analyzed, and a report is expected during the coming year.

Traveling Waves on Steep Slopes ($300). The work has been on a study of traveling waves and bores in a channel of trapezoidal cross section 92 feet long, with slopes from zero to about eight degrees.

Phenomena of Intersecting Streams ($300). The work on open channel intersections has been suspended for the present and attention is being directed to intersections of closed conduits. It was found that better results could be obtained by this procedure.

Curves in Open Channels ($300). Data have been taken on velocity measurements at various sections of the bend of a rectangular section 18 inches wide and of varying depth up to 10 inches. These data have been plotted into curves showing the condition of flow. A mathematical analysis of stream lines, angular velocity, and acceleration has been made in accordance with the laws of hydrodynamics.

Sedimentation at the Confluence of Rivers ($300). A new apparatus has been built at the St. Anthony Falls Hydraulic Laboratory designed to overcome some of the short-comings of the original experimental setup.

Alloys of Iron (AIME, $5,000). During the year the manuscript for "The Alloys of Iron and Nickel, Volume I" was completed. The first draft of "The Alloys of Iron and Chromium, Volume II" was finished and prepared for review by the co-operating experts. Work has been continued in assembling the data for "The Alloys of Iron and Nickel, Volume II—Engineering Steels," "The Alloys of Iron and Manganese," and "The Alloys of Iron and Vanadium."

Barodynamic Researches (AIME, $2,500). Work on this project has been continued. The following investigations were made:

1. The effect of immediate roof thickness in longwall mining.
2. The effect of artificial support in longwall support.
3. Stress distribution in mine pillars by photoelastic means.
4. Stress distribution in mine bottoms and roofs by photoelastic means.
5. Time effects in the behavior of rock structures stressed beyond the elastic limits.

Several articles have been published and others are to follow.

Critical Pressure Steam Boilers (ASME, $1,000). The 1937–38 research program has included viscosity of steam and oxidation of metal in contact with high-temperature steam. The viscosity study has confirmed previous results, and the effect of stress on intercrystalline corrosion is being studied.

Fluid Meters (ASME, $1,000). Tests of discharge through various sizes of nozzles have been made at four university laboratories, and the National Bureau of Standards.

Lubrication (ASME, $1,000). It was decided to discontinue some activities and to take up others. Compilation of the lubrication bibliography is progressing. The subcommittee on viscosity at high rates of shear is studying its problem. The committee proposes to investigate temperature distribution in bearings and pedestals during the coming year.

Cottonseed Processing (ASME, $500). Work done in 1936–37 demonstrated that definite benefits accrue from short-time cooking of cottonseed under steam pressure at elevated temperatures; the work of 1937–38 included a practical application of the cooking process using small equipment.

Rolling Steels (ASME, $900). It has been decided to base the research made upon tension test specimens. The heating will be done in an induction furnace designed to operate at suitable temperatures. The design of a machine, which will draw out the specimens at the necessary rapid speeds of deformation, has been begun.

Stability of Impregnated-Paper Insulation (AIEE, $2,000 plus $1,000). The principal purpose of the research is a study of the dielectric strength and stability of impregnated-paper insulation as related to the density of the paper. The schedule of progress originally outlined for the work has been maintained, tests on four out of the five grades of paper to be tested have been completed. It is anticipated that no difficulty will be met in completing the tests on the five grades of paper before the date originally set for the completion of the experimental work. The supervisory committee has indicated that it considers the results to be of value and interest, and has considered generally a desirable program for a continuation of the work through another year.

Welding Research Committee (AIEE and American Welding Society, $4,000 plus $5,900). The work of the welding research committee is becoming an established, recognized institution. Leading articles and research reports carry bibliographic references to reports or reviews issued by the welding research committee. So far, the work has been concerned largely with critical digests of the literature, making available translations of important articles to research workers and others interested, and the conduct of relatively small, but important, pieces of fundamental research in leading universities. This year, however, has witnessed the financing of one of the major projects of the industrial research division, namely, the fatigue strength of welded joints. A fellowship was created at Rensselaer Polytechnic Institute in resistance welding, and grants-in-aid have been given to several selected universities for support of specific researches. During the year a total of 452 printed pages were published as *Research Supplements* to the *Welding Journal*. Thirty translations have been made available.

Engineers Council for Professional Development ($3,750). The major activity has been a continuation of the accrediting of institutions and curricula. An advisory service to institutions has been worked out in further detail, and already several opportunities have been developed of assisting institutions. Over 15,000 copies of "Engineering: A Career—A Culture" have been sold. More colleges are showing an interest in the problems of more careful selection of engineering freshmen.

Plastic Flow of Concrete (University of California, $1,500). During this year, the more important results have been in connection with the extensibility of concrete under temperature conditions simulating those existing in mass concrete as it heats and cools; the relation of the quality of hardened cement paste to flow; the relation of the quality of hardened cement to flow; the relation between moisture loss and flow; and the fiber strains due to flow in beams. Work is progressing on tests of the effect of thermal stresses in walls and slabs; the effect of revibration on plastic flow; the effect of sustained stress on bond between concrete and steel; the plastic flow of concrete in shear; and the plastic flow of concrete during the early hardening period.

Personnel Research Federation ($1,200). The problems incident to negotiations with employees have been studied by interviews with operating and industrial relations executives and labor leaders, studying records of negotiations and the literature on the subject. It is expected to publish the results of the study in a series of articles during the next months.

Wind Direction and Velocity (New York University, $500). Some experimental pilot balloon ascents with 180-degree cameras were made. Perfect recording occurred up to over 2,000 feet altitude. No higher ascents have been made. It appears likely that reliable readings will be obtained with the new apparatus at such altitudes as are required in pilot balloon work.

More complete progress reports on the active research projects are on file in the office of The Engineering Foundation. A number of specific problems are under investigation over a wide range of subjects rather than a small number of more elaborate problems. Further information on the Foundation and its activities may be obtained at Foundation's office, 29 West 39th Street, New York, N. Y.

Personal Items

F. B. Jewett (A'03, F'12) has been awarded the 1939 John Fritz Gold Medal, highest of American engineering honors, for "vision and leadership in science, and for notable achievement in the furtherance of industrial research and development in communication." The award is made annually for notable scientific or industrial achievement by a board composed of representatives of the four national engineering societies of civil, mining and metallurgical, mechanical, and electrical engineers. Doctor Jewett was born at Pasadena, Calif., September 5, 1879, and received the degrees of bachelor of arts (1898) from Throop Polytechnic Institute (now California Institute of Technology) and doctor of philosophy (1902) from the University of Chicago. From 1904 to 1912 he was associated with the American Telephone and Telegraph Company as transmission engineer, and in 1916 became chief engineer of the Western Electric Company after serving four years as assistant to that position. He was made vice-president of the Western Electric Company in 1922, and since 1925 has been vice-president in charge of development and research of the American Telephone and Telegraph Company and president of Bell Telephone Laboratories, Inc., in New York, N. Y. Doctor Jewett was awarded the AIEE Edison Medal in 1928, and the Washington Award of the Western Society of Engineers for 1938. The degree of doctor of science has been conferred upon him by six universities, and the degree of doctor of engineering by one; he also has received other honors. Doctor Jewett was vice-chairman of The Engineering Foundation from 1919 to 1925 and chairman of the division of engineering and industrial research of the National Research Council from 1923 to 1927. A past-president of the AIEE, he has been active in its work and in that of other societies of which he is a member. He was a member of the committee on railway research of the Science Advisory Board appointed by President Roosevelt, and is a director of the National Advisory Council on Radio in Education.

H. B. Bryans (M'17, F'18) has been elected executive vice-president of the Philadelphia Electric Company, Philadelphia, Pa. Mr. Bryans was born at Philadelphia March 26, 1886, and was graduated from the University of Pennsylvania in 1907 with the degree of bachelor of science in mechanical engineering. Following graduation he was connected with the Philadelphia Gas Works, Kansas City (Mo.) Gas Company, and Fulton County Gas and Electric Company, Gloversville, N. Y. In 1912 he returned to Philadelphia as assistant to inspecting engineer with the United Gas Improvement Company, and two years later was appointed engineer of the Counties Gas and Electric Company at Norristown, Pa. In 1927 he was made general superintendent of the Philadelphia Suburban-Counties Gas and Electric Company and in the following year was promoted to assistant general manager of the same company. Mr. Bryans was then transferred to the Philadelphia Electric Company and was made vice-president in 1929.

J. M. Conroy (A'23) has become deputy chief engineer of the Canadian Marconi Company, Montreal, Que., Canada. Mr. Conroy is a native (1886) of Ottawa, Ont., and a graduate of McGill University, from which he received the degree of bachelor of science in electrical engineering. He was employed by the Canadian Westinghouse Company, Canadian General Electric Company, and the Department of Naval Service before he joined the Canadian Marconi Company in 1922. Since that time he has steadily advanced in the company's services and has held the position of works engineer for the past 11 years.

R. E. Powers (A'33) has been appointed northwestern district service manager for the Westinghouse Electric and Manufacturing Company. Mr. Powers, who was graduated from Washington State College in 1923 with the degree of bachelor of science in electrical engineering, has been employed continuously by the Westinghouse company since 1923. In 1926 he was transferred to the central station division of general engineering, and was engineering representative in the New York district, being made eastern engineering manager in 1936.

F. W. Smith (A'18, M'34) has been appointed general engineer of the Virginia Electric and Power Company, Richmond. Born at Northampton, Mass., September 7, 1888, Mr. Smith received the degree of bachelor of science in electrical engineering from Worcester Polytechnic Institute. He obtained his first experience in the public utility field with the New England Power Company in 1913, acting in various capacities until 1919, where he accepted a position with the Goodyear Tire and Rubber Company, Akron, Ohio. The following year he entered the employ of the Stone and Webster Engineering Corporation at Boston, Mass., and in 1921 was transferred to the Blackstone Valley Gas and Electric Company at Pawtucket, R. I. In 1931 he became assistant general engineer for the Virginia Electric and Power Company. Mr. Smith is secretary of the AIEE Virginia Section.

M. M. Samuels (F'24) has resigned from the Federal Power Commission to accept appointment as chief operations engineer of the Rural Electrification Administration, Washington, D. C. Mr. Samuels joined the Federal Power Commission in 1934 as technical adviser of the electric rate survey and later as electrical engineer in the regional office at New York, N. Y. While with the commission he participated in the preparation of numerous confidential reports. A native of Schaki, Lithuania, he was graduated from the Technical University of Karlsruhe in 1905, and was for 20 years on the staff of the J. G. White Engineering Corporation where he was responsible for the electrical engineering of numerous utility and industrial projects.

R. E. Williams (A'35) has become a member of the staff of the technical press service of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. A native (1912) of Mulberry, Ind., and a graduate of Purdue University, from which he received the degree of bachelor of science in electrical engineering in 1934, Mr. Williams had been a member of the Institute's publication staff since 1936. Prior to joining the Institute's staff he was a member of the electrical-engineering staff of Gibbs and Cox, Inc., marine and naval architects

M. M. SAMUELS

H. B. BRYANS

F. B. JEWETT

C. F. SCOTT

FRANCIS HODGKINSON

JAMES DIXON

at New York, N. Y. He was a member of the AIEE Student Branch at Purdue, and is an associate, Society of Sigma Xi, national research honorary fraternity.

James Dixon (A'02, M'13) has accepted the position of assistant general manager and chief engineer with the Elliott Company, Ridgway, Pa. Mr. Dixon was born at New York, N. Y., March 5, 1877, and was graduated from Columbia University in 1901 with the degree of electrical engineer. He then entered the employ of the Gray National Telautograph Company for five years, and in 1910, following work with the General Storage Battery Company at Boonton, N. J., became superintendent of construction and repair with the Crocker Wheeler Company at Ampere, N. J. He returned to the company after a short absence in 1915 as assistant chief engineer. In 1920 he became production manager with the Reliance Electric and Engineering Company, Cleveland, Ohio. For the past several years Mr. Dixon had again been affiliated with the Crocker Wheeler Company as engineer of test, inspection, and construction.

C. F. Scott (A'92, F'25, HM'29) has been elected president of the National Council of State Boards of Engineering Examiners. Doctor Scott is emeritus professor of electrical engineering, Yale University, New Haven, Conn., and has recently been devoting much time to matters pertaining to education and registration of engineers. From 1935 to 1938 he was chairman of Engineers' Council for Professional Development, and for 1937–38 was vice-president of the NCSBEE. For 1938–39 he has been appointed chairman of the ECPD committee on professional recognition. Doctor Scott is a past-president of the AIEE and received the Edison Medal in 1929; he has a long record of service in Institute affairs.

Francis Hodgkinson (A'02) consulting mechanical engineer, New York, N. Y., has been awarded the Holley Medal of The American Society of Mechanical Engineers for "meritorious services in the development of the steam turbine." Mr. Hodgkinson is widely known as a designer and builder of steam turbines, and is honorary professor of mechanical engineering at Columbia University. He was born in London, England, June 16, 1867, and was educated in England. He was associated with C. A. Parsons in the early development of the reaction turbine, and was superintendent of construction of C. A. Parsons and Company when, in 1896, a license agreement was negotiated with the late George Westinghouse and Mr. Hodgkinson was given charge of steam-turbine construction for the Westinghouse Machine Company. In 1916 he was made chief engineer of the Westinghouse Electric and Manufacturing Company, and ten years later became consulting engineer for the company, serving in that capacity until his retirement in 1936. Stevens Institute of Technology granted him the honorary degree of mechanical engineer in 1934.

W. H. Rodgers (A'24, M'30) has been appointed engineering manager of the eastern district of the Westinghouse Electric Manufacturing Company, with headquarters at New York, N. Y. After graduating from the University of Illinois in 1922, Mr. Rodgers entered the central station engineering section of the Westinghouse company at East Pittsburgh, Pa., and for nearly 15 years, until his present appointment, worked on electrical supply and distribution problems.

F. H. Doremus (A'24, M'32) has been appointed manager for the Rocky Mountain district of the transportation department of the General Electric Company at Denver, Colo.; he also is manager of the industrial department for that district. Mr. Doremus has been affiliated continuously with the company since graduation from the University of Nebraska in 1922, and was transferred to the industrial department at Denver in 1925.

W. H. Harrison (A'20, F'31) has been elected a member of the corporation of the Polytechnic Institute of Brooklyn. Vice-president and chief engineer of the American Telephone and Telegraph Company, New York, N. Y., he is a past president of the AIEE, and recently was granted the honorary degree of doctor of engineering as announced in the July 1938 issue.

Zay Jeffries (M'36) has been elected a member of the corporation of Case School of Applied Science, Cleveland, Ohio. Doctor Jeffries was a member of the faculty of the school from 1911 to 1917, and is an authority in metallurgy. He is now technical director of the incandescent lamp department of the General Electric Company at Cleveland.

B. S. Rodey, Jr. (A'22, M'26) has received the degree of doctor of judicial science after writing a thesis on the terms "original cost" and "prudent investment." Mr. Rodey is auditor with the Consolidated Edison Company of New York, Inc., New York, N. Y., and chairman of the general accounting committee of the Edison Electric Institute.

R. E. Doherty (A'16, M'27) has been elected vice-chairman of Engineers' Council for Professional Development for the year 1938–39. Doctor Doherty is president of Carnegie Institute of Technology, Pittsburgh, Pa., and is the recipient of the 1937 Lamme Medal, as announced on page 141 of the March 1938 issue.

J. H. Foote (A'18, F'32) has been elected chairman of the committee on copper and copper alloy wires for electrical conductors of the American Society for Testing Materials. Mr. Foote is supervising engineer with the Commonwealth and Southern Corporation, Jackson, Mich.

S. H. P. Wolferstan (M'35) has been appointed manager of the contract service department of the Canadian General Electric Company, Toronto, Ont. He formerly was district engineer for the company at Montreal, Que.

G. G. Post (A'11, F'33) has been elected president of the Engineers' Society of Milwaukee. Mr. Post is vice-president in charge of power, Milwaukee Electric Railway and Power Company, Milwaukee, Wis.

D. E. Culnan (A'37) has accepted a position as junior examiner in the electrical engineering division of the United States Patent Office at Washington, D. C. Mr. Culnan formerly was junior engineer with Fibreboard Products, Inc., Antioch, Calif.

Douglas Montgomery (A'26) has accepted a position as assistant electrical engineer with the Illinois Iowa Power Company, Champaign, Ill. Formerly he was electrical draftsman with the Detroit Edison Company, Detroit, Mich.

Norman Carlberg (A'38) is now junior engineer with the United States Navy Yard at Bremerton, Wash. He formerly was at Fort Peck, Mont.

J. R. Read (A'04) recently was elected a director of the Canadian Westinghouse Company, Hamilton, Ont. He is vice-president of the company.

E. J. Withers (A'34) now is employed in plant operations work for Hiram Walker and Sons, Inc., Peoria, Ill.

F. W. Frink (A'31) has become a radio engineer for the Radio Receptor Company, New York, N. Y.

L. E. Mathews (A'35) has been appointed assistant rate analyst for the Rural Electrification Administration, Washington, D. C.

W. J. Lind (A'36) has become an air conditioning engineer for the Canadian General Electric Company, Ltd., Vancouver, B. C.

E. H. Small (A'38) has been appointed instructor in mechanical engineering at the University of Toledo (Ohio).

Obituary

Walter Sherman Moody (A'06, M'10, F'12) retired transformer engineer, died November 7, 1938, at Pittsfield, Mass. Born at Chelsea, Mass., September 20, 1864, Mr. Moody in 1887 was a member of the first electrical-engineering class to graduate from Massachusetts Institute of Technology. He remained for one year as instructor, a period during which he met William Stanley at a demonstration of an a-c system and was impressed with the possibilities of a-c distribution. In 1888 Mr. Moody became assistant engineer of the Thomson Electric Welding Company, and in 1892 joined the staff of the Thomson-Houston Electric Company at Lynn as designing engineer in transformers and a-c dynamos. In that year the company merged with the General Electric Company and Mr. Moody was made chief engineer of the transformer department at Lynn. He was transferred to Schenectady, N. Y., in the same capacity in 1897, and in 1908 was placed in charge of transformer engineering for the entire company at Pittsfield. In 1927 he was named consulting engineer by the company, and in 1931 he retired from active work. Mr. Moody contributed many improvements in transformers and induction regulators, and did pioneer work in the use of silicon sheet steel in electrical equipment. He was one of the original members of the Institute's Pittsfield Section, and at one time was a representative on the United States National Committee of the International Electrotechnical Commission.

S. Clifford Jacoby (A'21, M'31) superintendent of transmission and distribution, Montaup Electric Company, Fall River, Mass., died October 20, 1938. Mr. Jacoby was born at Conshohocken, Pa., August 21, 1896, and was graduated from a course in engineering in 1917. He then accepted the position of student engineer with Stone and Webster, and was sent to Key West, Fla. Two years later he was transferred to the Blackstone Valley Gas and Electric Company at Pawtucket, R. I., where he was promoted through several positions. In 1925 he was made chief load dispatcher for the Montaup Electric Company, and three years later was promoted to the position of superintendent of transmission and distribution.

Harold Hutchison Shearer (M'20) directory engineer, American Telephone and Telegraph Company, New York, N. Y., died November 10, 1938. Mr. Shearer was born at Bay City, Mich., August 24, 1886, and studied at the University of Michigan, from which he was graduated in 1908 with the degree of bachelor of science in electrical engineering. He was then employed in the Long Island division of the New York Telephone Company, and in 1913 became division plant engineer. During 1917–19 he served as major and lieutenant colonel with the United States Army in France, and shortly after his return to the United States was transferred to the general engineering staff of the operations section of the American Telephone and Telegraph Company at New York. He had been directory engineer for the past ten years. Mr. Shearer was a member of Sigma Xi and Tau Beta Pi.

Kenneth Buchanan Thornton (A'01, M'13) general manager of Montreal Tramways Company, Montreal, Que., Canada, died February 10, 1938. He was born at Montreal June 26, 1873, and studied electrical and mechanical engineering at Central Technical College, London, England. From 1893 to 1895 he was associated with the Royal Electric Company and the Montreal Light, Heat and Power Company at Montreal, following which he became associated with J. G. White and Company, having various operating positions with companies in New York, Portland, Me., and Connecticut. In 1911 Mr. Thornton became chief engineer and operating manager for the Canadian Light and Power Company and its affiliated companies, in 1920 general manager of the Montreal Public Service Corporation, and in 1926 of the Montreal Tramways Company.

George Herbert Thrush, Jr. (A'34) manager of the Pittsburgh, Pa., branch of The Electric Storage Battery Company, died September 25, 1938. Mr. Thrush was a native of Shippensburg, Pa., where he was born September 25, 1894. From 1911 to 1919 he served in the United States Army, rising to the rank of captain and later becoming major in the Officers Reserve Corps. In 1919 he entered Gettysburg College, from which he was graduated in 1924 with the degree of bachelor of science in electrical engineering. For brief periods he was employed by the Bell Telephone Company of Pennsylvania; in 1924 he became sales engineer with The Electric Storage Battery Company. He held various positions in offices at Atlanta, Ga., New Orleans, La., and Pittsburgh, being appointed manager of the last branch in 1930.

Hugo P. Geisler, Jr. (M'36) appraisal manager, Stone and Webster Engineering Corporation, Boston, Mass., died September 10, 1938. Born at Saginaw, Mich., June 29, 1895, Mr. Geisler studied electrical engineering at Massachusetts Institute of Technology. In 1918 he joined the Stone and Webster organization, and subsequently held various positions in gas and electric companies operating in the states of Kentucky, Connecticut, Washington, and Louisiana. In 1927 he was made engineer in the appraisal division of the organization, and following several other advances was made appraisal engineer in 1930. Three years later he was given the title of appraisal manager and personal responsible charge of general appraisal work of the company involving properties having a value in excess of one billion dollars.

James P. Alexander (M'21) New England district manager for the Westinghouse Electric and Manufacturing Company, Boston, Mass., died October 8, 1938. He was born at Chambersburg, Pa., November 22, 1885, and was graduated from Lafayette College with the degree of electrical engineer in 1907. In that year he entered the employ of the Westinghouse company, and after completing the apprentice course entered the railway department at East Pittsburgh, Pa., remaining there until 1911 when he was transferred to the Boston office as railway engineer. In 1913 he became a railway salesman located in the Springfield, Mass., office and two years later went to the New Haven, Conn., office as railway and central station salesman. He was made manager of the transportation division at Boston in 1922 and manager of the New Haven branch office in 1924, returning to Boston ten years ago as manager in charge of all sales and service in New England.

Frederick Miles Bronson (M'36) engineer with the American Telephone and Telegraph Company, Washington, D. C., died October 23, 1938. Mr. Bronson was born at Walton, N. Y., May 11, 1882, and became manager of the Walton Telephone Company in 1900. Two years later he entered the engineering department of the New England Telephone and Telegraph Company at Boston, Mass., at subsequently held positions at Bangor and Portland, Me. In 1910 he became engineer in the engineering department of the American Telephone and Telegraph Company at New York, N. Y., where he had increasing responsibility in traffic engineering and operating problems. Mr. Bronson was transferred to Washington two years ago.

Watkins Franklin Mintzer (A'20) retired construction engineer, service department, Canadian Westinghouse Company, Ltd., Hamilton, Ont., Canada, died August 22, 1938. Mr. Mintzer was born at Croydon, Pa., December 3, 1889, and in 1908 entered the employ of a company manufacturing scientific instruments; after a short time he joined the Metropolitan Railway Company in New York, N. Y. In 1910 he accepted a position with the General Electric Company, and two years later became engaged in electrical construction work with the Canadian Westinghouse Company, an affiliation which he continued until his retirement in 1934.

James L. F. Bracken (A'18) designing engineer, New York, New Haven and Hartford Railroad Company, New York, N. Y., died October 21, 1938. Mr. Bracken was born October 10, 1893, and studied engineering at the Sheffield Scientific School of Yale University. In 1915 he entered an apprentice course in the electric locomotive shops of the New Haven Railroad, and two years later was made electrical draftsman. He became assistant electrical engineer in 1920, and in 1928 was transferred to New York as assistant to mechanical superintendent. A few years later he was made designing engineer.

Charles H. Harris (A'34) general engineer of the Virginia Electric and Power Company, Richmond, died October 22, 1938. He was born at Natick, Mass., and received the degree of bachelor of science from Massachusetts Institute of Technology in

1901. Upon graduation he joined the Stone and Webster organization at Boston, Mass., and subsequently held various positions with the Seattle Electric Company, Minneapolis General Electric Company, Mississippi River Power Company, Western United Company, and Tampa Electric Company. Mr. Harris had been with the Virginia Electric and Power Company since 1927.

Arnold Simeon Upley (A'37) electrical engineer, Chase-Shawmut Company, Newburyport, Mass., died recently. He was born at Roxbury, Mass., August 16, 1913, and received the degree of bachelor of science in electrical engineering from Northeastern University in 1936. As a co-operative student he was employed by The Edison Electric Illuminating Company of Boston in 1931–32, and in 1936 he entered the engineering department of the Chase-Shawmut Company where he was engaged in design and research on fuses.

Gisle Edwin Huseby (A'26) engineer, Illinois Bell Telephone Company, Chicago, died October 2, 1938. He was born at New Richland, Minn., November 27, 1898, and was graduated from the University of Minnesota with the degree of bachelor of science in electrical engineering in 1924. In that year he entered the employ of the Western Electric Company at Chicago as equipment engineer; a short time later Mr. Huseby became associated with the Illinois Bell Telephone Company.

Montgomery Ralston Bird (A'36) tester, General Electric Company, Bloomfield, N. J., died November 27, 1936, according to word just received at Institute headquarters. Mr. Bird was born at North Plainfield, N. J., December 29, 1910, and was graduated from the Newark College of Engineering in 1935 with the degree of bachelor of science in electrical engineering. Early in 1936 he entered the employment of the General Electric Company as a tester in the air-conditioning department.

Raymond Guttmann (A'35) Albany, N. Y., died February 22, 1938. Mr. Guttmann was born at Schoharie, N. Y., August 30, 1911, and was graduated from Rensselaer Polytechnic Institute in 1934 with the degree of electrical engineer.

Membership

Recommended for Transfer

The board of examiners, at its meeting on November 17, 1938, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Piatt, Wm. M., consulting engineer, Durham, N. C.
Race, H. H., research engineer, General Electric Company, Schenectady, N. Y.

2 to Grade of Fellow

To Grade of Member

Fies, John, assistant to head of distribution department, Dallas Power & Light Company, Dallas, Texas
Ghen, M. W., superintendent, downtown division, Duquesne Light Company, Pittsburgh, Pa.
Janes, C. W., instructor in electrical engineering, University of Arkansas, Fayetteville.
Maxfield, F. A., instructor in electrical engineering, University of Wisconsin, Madison.
Nuezel, E. F., superintendent, underground electrical transmission and distribution department, Cincinnati Gas & Electric Company, Cincinnati, Ohio
Sessoms, O. V. P., superintendent, meter and installation department, Virginia Electric & Power Company, Richmond, Va.
Sixtus, E. F., vice-president in charge of sales, Pacific Electric Manufacturing Corporation, San Francisco, Calif.
Sturtevant, G. R., meter engineer, General Electric Company, West Lynn, Mass.

2 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before December 31, 1938, or February 28, 1939, if the applicant resides outside of the United States or Canada.

United States and Canada

Abraham, L. G. (Member), Bell Telephone Laboratories, Inc., New York, N. Y.
Arning, H. U., Otis Elevator Company, New York, N. Y.
Austry, W. H. (Member), Stackpole Carbon Company, St. Marys, Pa.
Balacek, F. P., Bell Telephone Laboratories, Inc., New York, N. Y.
Booth, R. H., Worthington Pump and Machinery Corporation, Seattle, Wash.
Bunten, G. E., Bureau of Power and Light, Los Angeles, Calif.
Carter, C. W., Jr. (Member), Bell Telephone Laboratories, Inc., New York, N. Y.
Christensen, E. F., General Electric Company, Pittsfield, Mass.
Clemens, G. J., City College of New York, New York, N. Y.
Clements, S. E., Iowa State College, Ames.
Cookman, F. W., Portland General Electric Company, Portland, Ore.
Couch, W. H., Hickok Electrical Instrument Company, Cleveland, Ohio.
Davis, J. I. (Member), Commonwealth Edison Company, Chicago, Ill.
de Carvajal, C. A. R., National Broadcasting Company, New York, N. Y.
Diller, H. N., Ohio Public Service Company, Mansfield.
Dillon, H. M., Nelson Electric Supply Company, Oklahoma City, Okla.
Dlouhy, F. S., Oklahoma Gas and Electric Company, Oklahoma City.
Doolittle, J. W., Southwestern Bell Telephone Company, Oklahoma City, Okla.
Dwyer, R. C., Bonneville Project, Portland, Ore.
Ennis, J. G., Florida Power and Light Company, Miami.
Gandy, T. O., Oklahoma Gas and Electric Company, Ardmore.
Gartner, H. C., Cincinnati Gas and Electric Company, Cincinnati, Ohio.
George, E. L., Southern Bell Telephone and Telegraph Company, New Orleans, La.
Glidewell, J. A., Western Union Telegraph Company, Dallas, Texas.
Greenleaf, E. R., The Chesapeake and Potomac Telephone Company, Washington, D. C.
Griffin, W. H. (Member), Southwestern Creosoting Company, Muskogee, Okla.
Hachemeister. C. A., City College of New York, New York, N. Y.
Hall, E. R., General Electric X-Ray Corporation, San Francisco, Calif.
Harding, W. K., Duke Power Company, Charlotte, N. C.
Hartman, T. W., Cleveland Public Schools and Fenn College, Cleveland, Ohio.
Haynes, H., General Electric Company, Cleveland. Ohio.
Hayward, H. O. F., British Columbia Electric Railway Company, Vancouver, B. C., Canada.
Hendricks, R. M., Southern New England Telephone Company, New Haven, Conn.
Hinshaw, E. G., Indiana Bell Telephone Company, Indianapolis.
Hobbs, W. E., Chesapeake and Potomac Telephone Company, Richmond, Va.
Hofer, H. T., Public Service Company of Colorado, Denver.
Hoover, J. W., International Business Machines Corporation, Endicott, N. Y.
Jahn, E., J. G. White Engineering Corporation, New York, N. Y.
King, R. E., Consolidated Edison Company of New York, Inc., New York, N. Y.
Kraus, C. R., Bell Telephone Company of Pennsylvania, Philadelphia.
LaDieu, W. L., Delgado Central Trades School, New Orleans, La.
Limpus, L. M., Oklahoma Gas and Electric Company, Oklahoma City.
Llewellyn, M. R., Southern Utah Power Company, Cedar City, Utah.
Mackie, F. W., Southwestern Light and Power Company, Lawton, Okla.
Million, E. J., Southwestern Light & Power Company, Clinton, Okla.
Moench, T. S., American Telephone and Telegraph Company, Buffalo, N. Y.
Morningstar, M. B., E. 2013 Mallon Avenue, Spokane, Wash.
Moses, B. S., Pacific Gas and Electric Company, San Francisco, Calif.
Muir, W. L., Nelson Electric Supply Company, Oklahoma City, Okla.
Neal, E. F., Southwestern Light and Power Company, Lawton, Okla.
Nichols, C. E., Tennessee Valley Authority, Knoxville, Tenn.
Nicholson, A. J., Kansas City Power and Light Company, Kansas City, Mo.
Patterson, J. McG., Delgado Trade School, New Orleans, La.
Pearman, M. N., Chesapeake and Potomac Telephone Company, Richmond, Va.
Pickrell, D. H., Southwestern Bell Telephone Company, Oklahoma City, Okla.
Pierce, H. F. (Member), Maurice H. Connell and Associates, Miami, Fla.
Poillion, C. B., Delgado Central Trades School, New Orleans, La.
Plumley, H. J., Commonwealth Edison Company, Chicago, Ill.
Roth, J. D., Ohio Carbon Company, Cleveland.
Rubel, W. L. (Member), Memco Engineering and Manufacturing Co., Long Island City, N. Y.
Rudden, F. J., Memco Engineering and Manufacturing Company, Inc., Long Island City, N. Y.
Ryan, J. A. (Member), 4 Irving Place, New York, N. Y.
Schricker, J. L., General Electric Supply Corporation, Salt Lake City, Utah.
Schwarz, J., Brooklyn Edison Company, Brooklyn, N. Y.
Secord, R. E., Narragansett Electric Company, Providence, R. I.
Simmons, R. P., Cowles and Company, Dallas, Texas.
Snider, F. C., Hickok Electrical Instrument Company, Cleveland, Ohio.
Steck, H. L., Southern California Edison Company Ltd., Long Beach, Calif.
Taylor, J. J. (Member), Detroit Edison Company, Detroit, Mich.
Thomas, G. B., Jr., New York University, New York, N. Y.
Thomson, R. E., Henderson County Rural Electric Association, Henderson, Ky.
Vanoli, J. J., Consolidated Edison Company of New York, Inc., New York, N. Y.
Walton, A. W., Oklahoma Gas and Electric Company, Oklahoma City.
Wells, C. H., General Electric Co., Pittsfield, Mass.
Wheeler, W. R. (Member), American Telephone and Telegraph Company, Philadelphia, Pa.
Whitehouse, A. B. (Member), Lynn Gas and Electric Company, Lynn, Mass.
Withington, W. G., General Electric Company. Baltimore, Md.
Wittenburg, H. W., Sangamo Electric Company, Los Angeles, Calif.
Zabaro, D., Bureau of Power and Light, Los Angeles, Calif.

Total, United States and Canada—79

Elsewhere

Chakraverty, N. C., Nowrosjee Wadia College, Poona, India.
Currie, J. A. (Member), C. A. Sothers Ltd., Bham, England.
Dubusc, R. P. (Member), Cie. pour la Fabrication des Compteurs, Montrouge (Seine), France.
Jain, I. D., The British Insulated Cables Ltd., Calcutta, India.
Krishnaswami, P., C. N. Technical Institute, Madras, India.
Porter, J. H., Metropolitan Vickers Company Ltd., Manchester, England.
Ratnasabapathy, V., 86 Central Avenue, Calcutta, India.
Warder, S. B. (Member), Southern Railway Company Waterloo, London, England.

Total elsewhere—8

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Barrett, Earl J., Don Pedro Dam, La Grange, Calif.
Black, Kenneth H., 916 Yale Ave., S., Seattle, Wash.
De Lay, R. E., 77 Prospect Ave., Long Beach, Calif.
Gademann, Oscar M., Stuttgarterplatz 1A-11 Berlin-Charlottenburg, Germany
Hutchison, Paul C., 529 N. 13th St., Milwaukee, Wis.
Hyman, Stanley L., 156 Medway St., Providence, R. I.
Kapell, Sidney M., 3043 Emmons Ave., Brooklyn, N. Y.
Phillips, Cary Albert, Box 80-A, Route 6, Richmond, Va.
Platterer, Alvin, 776 N. Cass St., Milwaukee, Wis.
Robison, R. L., 941 E. Northlake Ave., Seattle, Wash.
Shimp, Robert P., 414 Hampton Ave., Wilkinsburg, Pa.
Whitney, T. G., Electrical Research Products, Inc., 250 W. 57th St., New York, N. Y.
Wilson, Alexander, 315 New Birks Bldg., Montreal, Que., Can.

13 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Society Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

DEMONSTRATION EXPERIMENTS in PHYSICS. Edited by R. M. Sutton, prepared under the auspices of the American Association of Physics Teachers. New York and London, McGraw-Hill Book Company, 1938. 545 pages, illustrated, 9 by 6 inches, cloth, $4.50. A collection of lecture experiments for the use of high school and college teachers of physics and general science.

TRANSFORMER ENGINEERING. By L. F. Blume, G. Camilli, A. Boyajian and V. M. Montsinger; edited by L. F. Blume. New York, John Wiley and Sons, 1938. 496 pages, diagrams, charts, tables, 9 by 6 inches, cloth, $5.00. Designed to assist engineers in the specification, selection, application, and operation of transformers. Emphasizes the essential physics of each problem.

TRANSFORMATOREN mit STUFENREGELUNG UNTER LAST. By K. Bölte and R. Küchler. Munich and Berlin, R. Oldenbourg, 1938. 182 pages, illustrated, 10 by 6 inches, cloth, 9.60 rm. Discusses the theory, construction, and use of transformers equipped with tap changers.

ENGINEERING MECHANICS. By S. Fairman and C. S. Cutshall. New York, John Wiley and Sons, 1938. 267 pages, diagrams, tables, 9 by 6 inches, cloth, $2.75. Presents only as much material as can be covered conveniently in a basic course. Contains the customary treatment of statics and kinetics, numerous problems being included.

DECIBELS and PHONS, a Musical Analogy. By L. S. Lloyd. London, New York, and Toronto, Oxford University Press, 1938. 18 pages, tables, 9 by 6 inches, paper, $0.50. An explanation of the meaning of the terms "phon" and "decibel" by considering the phon as a loudness-interval, comparable to the musical interval of a major third, and the decibel as representing the energy-interval which produces the phon.

BIBLIOGRAPHY on INDUSTRIAL RADIOGRAPHY. (Document 1139.) By H. R. Isenburger, Washington, D. C., American Documentation Institute, 1938. 52 pages, typewritten, 12 by 9 inches, paper, $0.72 in microfilm, or $3.32 in black and white prints. Supplement to St. John and Isenburger's book, "Industrial Radiography"; contains 776 references, arranged chronologically, covering material from early 18th century general theory to recent applications.

ATOMIC STRUCTURE. By L. B. Loeb. New York, John Wiley and Sons, 1938. 446 pages, illustrated, 9 by 6 inches, cloth, $4.50. Intended to supplement a basic course in physics and to provide students who have a working knowledge of calculus with a thorough grounding in atomic structure.

APPLIED MECHANICS. By H. F. Girvin. Scranton, Pa., International Textbook Company, 1938. 336 pages, diagrams, tables, 9 by 6 inches, cloth, $3.00. So arranged that the chapters covering graphical solutions may be used as a text for a course in graphic statics, being segregated from the purely mathematical treatment.

ADVANCED MATHEMATICS for ENGINEERS. By H. W. Reddick and F. H. Miller. New York, John Wiley and Sons, 1938. 473 pages, diagrams, charts, tables, 9 by 6 inches, cloth, $4.00. Discusses differential equations, vector analysis, probability, operational calculus, and the more complex mathematical functions and series, emphasis being placed on physical applications by illustrating each principal topic by problems relating to civil, electrical, mechanical, and chemical engineering.

WIRELESS SERVICING MANUAL. By W. T. Cocking. Fourth revised edition. London, The Wireless World, Iliffe and Sons, Ltd., 1938. 278 pages, illustrated, cloth, 5s. 5d. Covers the principles and practice of the repair and adjustment of wireless receivers. A chapter is devoted to television receivers.

VDI-JAHRBUCH 1938. Die Chronik der Technik, edited by A. Leitner of VDI. Berlin, VDI-Verlag, 1938. 312 pages, 8 by 6 inches, paper, 3.50 rm. Contains nearly 100 reports on developments during 1937 in various branches of engineering and technology.

TECHNICAL PROGRESS and UNEMPLOYMENT. Studies and Reports, Series C (Employment and Unemployment) No. 22. By E. Lederer. Geneva, Switzerland, International Labor Office, 1938. 267 pages, tables, 10 by 7 inches, paper, $1.50 (obtainable from United States branch, Washington, D. C.). An analysis of the social and economic effects of technical progress, especially on unemployment and the formation of capital. Discusses the various forms of technical progress, the concept of technological unemployment, increasing and diminishing returns, the equilibrium of the labor market, the effects of technical progress on the economic system and the labor and capital market, the elasticity of modern monetary systems, technical improvements and the business cycle, and capital-saving technical improvements.

(The) SCIENCE of PRODUCTION ORGANIZATION. By E. H. Anderson and G. T. Schwenning. New York, John Wiley and Sons, 1938. 282 pages, 9 by 6 inches, cloth, $3.50. Devoted mostly to the physical organization of work through operation study or job analysis and to the various types of organization of workers within small departments, plants, or whole enterprises. Discusses briefly larger aspects of the production problem.

RADIO LABORATORY HANDBOOK. By M. G. Scroggie. London, Wireless World, Iliffe and Sons, 1938. 384 pages, illustrated, 8 by 5 inches, cloth, 8s. 6d. Prepared with special consideration of the needs of amateurs and laboratory workers. Discusses fundamental principles, sources of power and signals, measurements, and certain specialized types of work, such as ultrahigh frequency.

PHOTOELECTRIC CELL APPLICATIONS By R. C. Walker and T. M. C. Lance. Third edition. New York and Chicago, Pitman Publishing Corporation, 1938. 336 pages, illustrated, 9 by 6 inches, cloth, $4.00. Restricted to discussion of the alkali-metal cell (with some reference to the rectifier cell). Describes the circuits used in counting and handling devices, alarms, sound reproduction, phototelegraphy, television, and miscellaneous applications.

MARCONI, the Man and His Wireless. By O. E. Dunlap, Jr. Revised edition. New York, Macmillan Company, 1938. 362 pages, illustrated, 9 by 6 inches, cloth, $3.50. The life of Marconi is portrayed against the background of his invention. The resulting biography constitutes a history of radio as well.

ENGINEERING TERMINOLOGY, Definitions of Technical Words and Phrases. By V. J. Brown and D. G. Runner. Chicago, Gillette Publishing Company, 1938. 310 pages, illustrated, diagrams, 9 by 6 inches, cloth, $3.50. A list of terms often used in technical writing and specifications, with definitions obtained from the usage of various trade and engineering organizations. The terms apply especially to civil engineering and architecture. Contains also a concise Spanish-English and English-Spanish dictionary of highway terms, a brief German-English dictionary of terms for mineral aggregates, and several tables of technical symbols, abbreviations, and conversion factors.

ELECTROMAGNETICS. By A. O'Rahilly, with a foreword by A. W. Conway. London, New York, and Toronto, Longmans, Green, and Company, 1938. 884 pages, diagrams, tables, 9 by 6 inches, cloth, $12.50. A critical review of the classical theory of electricity, discussing fundamentals, and the work of the men who have had an important influence on the thought and action in this field of physics. Contains two chapters in which a radical exposition of the meaning of the symbols of physics is worked out and the question of basic units and dimensions is discussed.

ELECTRIC POWER CIRCUITS, Theory and Applications. Volume 2. POWER SYSTEM STABILITY. By O. G. C. Dahl. New York and London, McGraw-Hill Book Company, 1938. 698 pages, diagrams, charts, tables, 10 by 6 inches, cloth, $7.00. Contains several chapters on each of the following topics: steady-state power limits, steady-state stability and transient stability, considering carrying conditions and different methods of analysis. Other chapters cover load characteristics, circuit equations for faulted networks, exciter analysis, damper windings, inertia, and grounding.

EDISON'S OPEN DOOR. By A. O. Tate. New York, E. P. Dutton and Company, 1938. 320 pages, 9 by 6 inches, cloth, $3.00. An informal account of Edison during one of the most dramatic periods of his life, based upon personal knowledge. Many other interesting characters and events are discussed.

DIRECT-CURRENT MACHINERY. By T. C. McFarland. Scranton, Pa., International Textbook Company, 1938. 439 pages, diagrams, charts, tables, 9 by 5 inches, leather, $4.00. Physical pictures of the assemblies are first presented, then operating characteristics and control, proceeding from no-load characteristics to load characteristics are discussed. Material on the no-load saturation curve and armature reaction is included.

GASEOUS ELECTRICAL CONDUCTORS. By E. L. E. Wheatcroft. Oxford, England, Clarendon Press; N. Y., Oxford University Press, 1938. 265 p., illus., 10 by 6 in., cloth, 21s. $6.50 U.S.A. For the technical man interested in vacuum tubes and similar apparatus; discusses first the fundamental facts of atomic structure, ionization, and emission. Succeeding chapters cover modern views on the nature of glow, corona, arc and spark, and final chapters deal with the application of the principles to various types of apparatus, such as vacuum and gas-filled tubes, rectifiers, circuit-breakers, and lamps.

Engineering Societies Library

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Papers Presented at North Eastern District Meeting, Lenox, Mass., May 18–20, 1938

No.	Authors	Titles of Papers (Some Shortened)
☐ 38-40	McEachron	*Multiple Lightning Strokes—II
☐ 38-41	Lennox & DeBlieux	*A Direct-Current Transformer
☐ 38-42	LaPierre & Mansfield	*Photoelectric Weft-Straightener Control
☐ 38-44	Sporn & Gross	*Protector-Tube Application and Performance on 132-Kv Lines—II
☐ 38-45	Brosnan	*System Planning and Operation for Voltage Control
☐ 38-46	Benner & Lunge	*Voltage-Regulating-Equipment Characteristics
☐ 38-47	Landis	*Voltage Regulation and Control of Rural Lines
☐ 38-48	Burrell & Appleton	*The Periodic Voltage Survey as a Basis for Distribution Design
☐ 38-49	Rogers	*Regenerative Tension Control for Paper Winders
☐ 38-50	Bendz	*Comparison of Methods of Stopping Squirrel-Cage Induction Motors
☐ 38-51	Von Sothen	*The Application of Capacitors in Industrial Plants
☐ 38-52	Vogel	*Corona Voltages of Typical Transformer Insulation

Papers Presented at Summer Convention, Washington, D. C., June 20–24, 1938

☐ 37-58	Smith & Weygandt	*Double Line-to-Neutral Short Circuit of an Alternator
☐ 37-866	Appleman	*The Cause and Elimination of Noise in Small Motors
☐ 38-53	Calvert	Amplitudes of the MMF Harmonics for Fractional Slot Windings
☐ 38-54	Porter	*Positive-Grid Characteristics of Triodes
☐ 38-55	Bewley	Traveling Waves Initiated by Switching
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* These papers have been published in the TRANSACTIONS section of ELECTRICAL ENGINEERING.

Transactions

Papers and Discussions Comprising Pages 359–422 of the 1938 Volume

Design and Test of High-Speed High-Interrupting-Capacity Railway Circuit Breaker

By WILFRED F. SKEATS
MEMBER AIEE

THIS PAPER describes an oil circuit breaker built to the following specifications:

Rated voltage	15,000 volts
Rated current	1,500 amperes
Frequency	25 cycles
Interrupting capacity	65,000 amperes
Over-all duration of short circuit	1 cycle

Being intended for railway trolley service, which is rather severe from the standpoint of frequency of short-circuit operation, it is expected to handle 50 short-circuit operations without internal inspection or change of oil.

Like breakers of somewhat lower interrupting rating previously supplied for this type of duty,[1] this breaker operates upon the impulse principle. A spring-driven piston forces a blast of oil across the arc, bringing about its extinction with a very small contact separation, and thus resulting in an arc of very short duration. The arrangement differs from that previously used in two important respects:

1. The earlier breakers used the radial blast, in which the oil moves in radially upon the arc and exhausts through a hole in one of the contacts; the present breaker employs the cross blast, in which a passage causes the oil to sweep directly across the arc path.
2. In order to supplement the action of the piston at high currents, a short pressure-generating break has been added. A check valve is employed to prevent the additional pressure from this break from being expended in reversing the piston.

The manner in which these operations are performed is shown in figure 1, which is a sectional view of the lower part of the breaker. While the breaker is in the closed position, the moving contact *1* presses against the intermediate contact *2*, holding it, in turn, against the stationary contact *3*. The piston *4* is at the upper end of its stroke. Upon tripping, the moving contact moves rapidly upward and the intermediate contact follows to the limit of its stroke. At the same time, force is applied to the piston and at moderately low current values it starts downward, forcing oil ahead of it down the piston cylinder up through the check values *5*, through the contact chamber, and through the horizontal passage *6* in the baffle *7*. This passage leads the oil directly across the arc path at *8* and exhausts both oil and gases from the arc into the air space at *9*. The velocity of the oil through the cross-blast passage is augmented slightly by the action of the pressure-generating break.

At high currents, the performance differs in that the pressure generated by the pressure-generating break is greater than that caused by the piston. The pressure-generating break then supplies all of the oil for the blast and the check valves remain closed and so prevent oil from the contact chamber from flowing down through them instead of through the cross-blast passage.

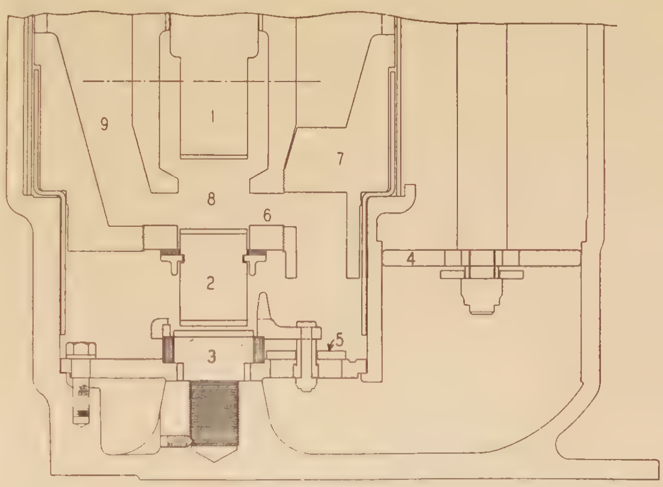

Figure 1. Sectional view of piston and interrupting element

Control of the length of the pressure-generating arc is accomplished, as shown in figure 2, by means of the metal ring *2* placed around the stationary contact *1* and so arranged that any current brought to it by the arc is led radially outward as indicated by the arrows. When the arc strikes the ring, this current path sets up a magnetic field which tends to move the arc back to the stationary contact. Thus the length of the arc can never greatly exceed the separation of the contacts.

Paper number 37-163, presented at the AIEE Middle Eastern District meeting, Akron, Ohio, October 13–15, 1937, and recommended for publication by the AIEE committee on protective devices. Manuscript submitted October 13, 1937; released for publication April 2, 1938.

WILFRED F. SKEATS is technical assistant to engineer, General Electric Company, Philadelphia, Pa.

[1] For numbered reference, see end of paper.

The mechanism is similar in principle to that used in the earlier breaker. It is shown schematically in figure 3. Energy for both the closing and opening operations, as well as contact pressure in the closed position, is supplied by the spring *1*. When the breaker is charged and open, this spring is restrained by the cam *2* operating through the pitman crank *3* and the pitman *4* to support pin *5*, and in combination, a stop limiting the upward motion of the contact rod. In order to close the breaker, the cam is rolled over the top, releasing the pin *5*. Roller *7* is now supported by the prop *6* but the links are free to move in a general downward direction until the contacts meet.

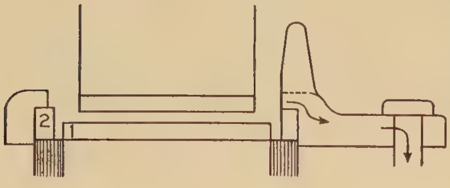

Figure 2. Arc-control arrangement at pressure-generating break

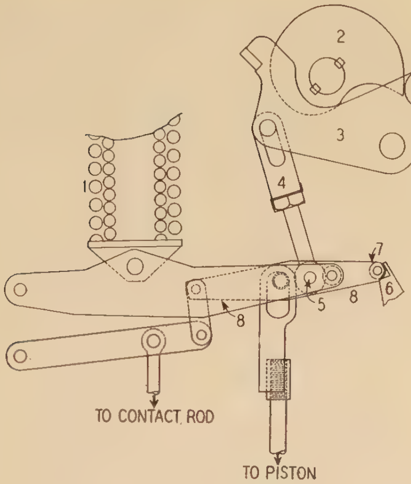

Figure 3. Mechanism in charged position

Then when the breaker is tripped open, the prop *6* is pushed out of position and the link *8* is free to rotate in a clockwise direction under the influence of the spring. This gives rise to an upward force on the contact rod, separating the contacts, and a downward force on the piston, creating the oil blast.

Immediately following the opening operation, a motor operating through a gear reduction mechanism turns the cam through about 300 degrees, which recharges the spring, placing the breaker in position to be reclosed in about seven seconds from the time of tripping.

The breaker and its control panel are assembled in the factory in a steel housing, with a door in front opening into the breaker compartment and a door in the rear opening upon the control panel. Figures 4 and 5 show the front and rear views with the doors open.

The testing of this breaker presented an interesting problem. In a one-cycle breaker, the severity of the duty is associated, to a large extent, with what may be called the waiting period, that is, the period after the breaker has set up conditions for clearing and while it is waiting for a current zero. It is obvious that the duration of this period is largely dependent on the frequency. Hence it is essential that the test frequency be the same as that at which the breaker is to be applied. As this was only 25 cycles while the normal testing-plant frequency is 60 cycles, the testing-plant generator had to be slowed down to about 40 per cent of its normal speed with a corresponding reduction in the output. Under these conditions the power available from the plant by the conventional testing circuit was only about 30 per cent of the breaker rating.

To overcome this situation, a special testing circuit similar to that used on the 287-kv breakers for the Boulder Dam–Los Angeles transmission line was employed. In addition to the breaker under test and the generator, this circuit comprises an auxiliary breaker with the same characteristics as the breaker under test, a transformer, a sphere gap, and, for the present tests, a synchronous closing switch, all arranged as shown in figure 6. The operation of this circuit is as follows. Initially the auxiliary breaker and the test breaker are in the closed position, and the synchronous closing switch is open. In order to initiate the short circuit, the synchronous closing switch is closed, and current flows through the auxiliary breaker, the test breaker, and the synchronous closing switch in series, and the full short-circuit current of the 3,000-volt generator connection is available. The test breaker and the auxiliary breaker both trip promptly and, in about three-quarters of a cycle, both set up conditions to clear the circuit on the next current zero.

With the breakers operating according to specification, the circuit is cleared in both at this current zero and in a few microseconds the voltage at the generator terminals

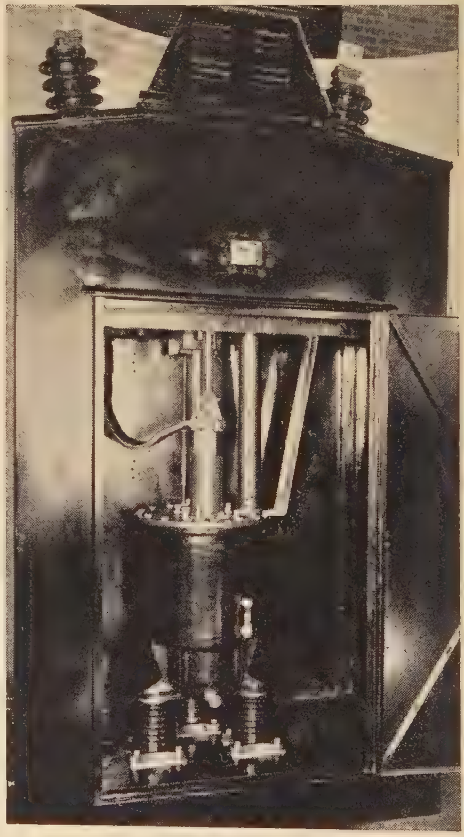

Figure 4. Breaker assembled in housing

has risen to approximately its normal peak value. This voltage is also applied at the low voltage terminals of the transformer, stepped up by the transformer in accordance with its ratio, and applied to the gap combination. This is sufficient to break down the gap and the transformer voltage is then applied to a point between the two breakers. Thus it appears directly across the test breaker. This entire process takes place, as shown by the cathode-ray oscillograph, within about 25 microseconds after the current reaches its zero value, or in about half the time required for the 10,000-cycle recovery transient to reach its first peak.

Thus, except for a period of about 25 microseconds during which no current normally flows and the voltage across the breaker is comparatively low, current interrupted by the breaker and recovery voltage are the same as in an operation at full voltage and full current.

For proper operation of the circuit, it is necessary that the gap combination should not break down appreciably before the time of current zero, and as the arc voltage when stepped up by the transformer ratio, had occasional voltage surges comparable with the recovery voltage in magnitude, a special gap arrangement was introduced to insure proper operation.

The design of this arrangement was facilitated by the fact that the breaker always interrupted after either one or two loops of current, according to the point on the voltage wave at which the short circuit struck. Since both the point on the voltage wave and the polarity of the first loop of short-circuit current were subject to control by the synchronous closing switch, it will be obvious that the polarity of the last loop was likewise controllable. The gap arrangement consisted of two sphere gaps in series shunted by equal resistances of about 120,000 ohms, but one of the two gaps was also shunted by a resistance of 1,000 ohms in series with a rectifier, the polarity of the rectifier being made such as to prevent current flow in response to arc voltage, but to permit flow in response to recovery voltage, which is of the opposite polarity.

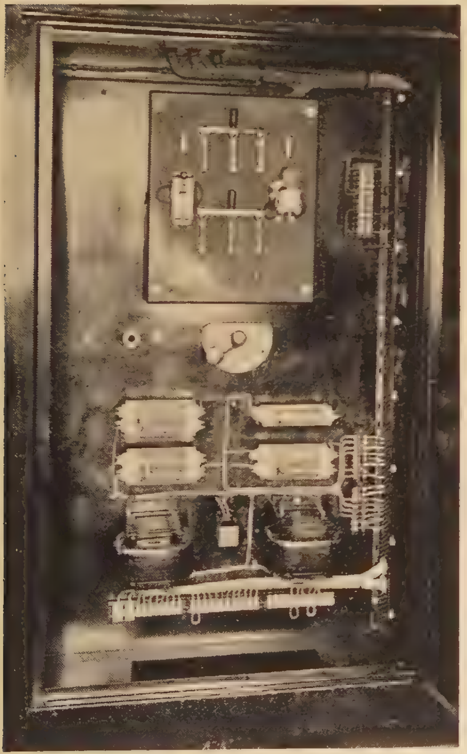
Figure 5. Rear view of housing showing control panel

Thus during the arcing period, the voltage is substantially equally divided between the two gaps by the higher resistances and the combination has a maximum breakdown strength. For the recovery voltage, however, one gap is shunted by a resistance of only 1,000 ohms, so that practically all of the applied voltage appears across the other gap. When this gap breaks down, the transformer supplies voltage to the breaker through a resistance of 1,000 ohms, which is low enough so that the drop across it is negligible, and thus, in effect, the gap combination breaks down on recovery voltage at about half the value required on arc voltage. As a matter of interest, the second gap usually breaks down either immediately or after about 50 microseconds when the voltage is falling in the second half of the first recovery oscillation.

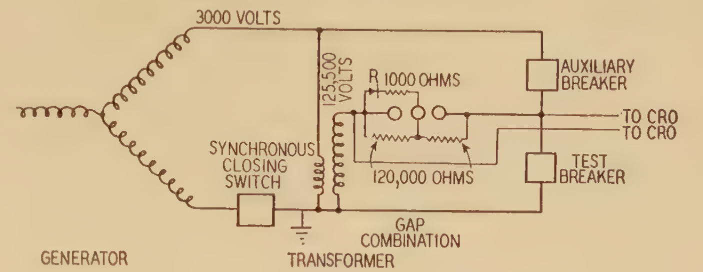

Figure 6. Special testing circuit

The magnetic oscillograms of figure 7 and the cathode-ray oscillogram, figure 8, indicate the performance of both breaker and circuit. Curves 3 and 6 show the short-circuit current, which has a very small minor loop followed by a large major loop. Within 0.05 cycle after the start of the major loop, the trip current responds, and at 0.6 cycle, motion of the contact rod starts (curve 2). Pressure (curve 7) is quickly generated by the primary break, and at the end of the first cycle the circuit is cleared. Curve 5 shows the voltage across the breaker, and it will be noted that the appearance of the curve immediately after interruption is no different from that corresponding to a conventional test at 12,500 volts.

The application of voltage to the breaker immediately after interruption is shown in more detail by the cathode-ray oscillogram. Two curves are shown on this record. The lower curve shows the voltage at the transformer side of the gap. Irregular oscillations occur in this curve during the arcing period; then, at the cessation of current, the voltage changes its polarity and swings into the recovery oscillation. A slight discontinuity is noticeable in this curve as it rises to the first peak of this recovery oscillation. This indicates the time of breakdown of one gap. Another discontinuity slightly after the peak indicates the breakdown of the second gap.

The upper curve shows the voltage across the breaker. During the arcing period, the deflection is barely perceptible. As the recovery voltage rises, however, the first gap breaks down and from that time on, except for a short time after the first peak when the breaker voltage is somewhat higher than the transformer voltage, the breaker voltage follows the same course as that of the voltage on the transformer side of the gaps. Thus the only period after current zero during which the voltage across the breaker is not at least as severe as that encountered on a 12,500-volt test is a very short time during the early part of the recovery oscillation when both voltages are comparatively low.

In a one-cycle breaker, the severity of the duty in a given test is likely to be a function of the point on the voltage wave at which the short circuit strikes and may be the greatest at a point on the wave quite different from that which gives maximum displacement to the current wave, or maximum root-mean-square value of the total current.

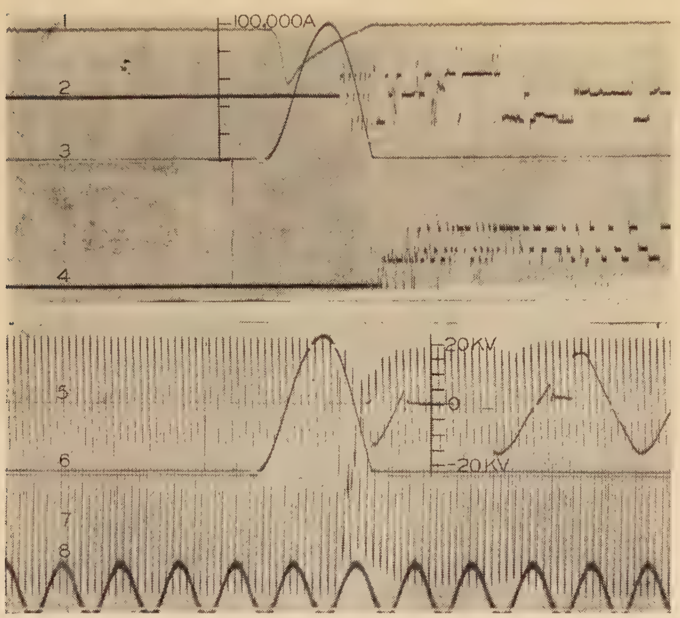

Figure 7. Magnetic oscillograms of an interruption at 12,500 volts, 60,000 amperes by special testing circuit

Curve 1—Trip-coil current
Curve 2—Contact travel: one-fifteenth inch per step
Curve 3—Current through breaker
Curve 4—Piston travel: one-fifteenth inch per step
Curve 5—Voltage across breaker
Curve 6—Current through breaker
Curve 7—Pressure in contact chamber
Curve 8—Timing wave—60 cycles

This was the case with the present breaker, and may be explained roughly as follows.

It may be expected that the severity of the duty will be a more or less direct function of the gas generation. This will depend approximately upon the ampere-seconds from the time of contact separation to the time of interruption, which will usually be the next current zero. Now when there is decay of the d-c component, as is always the case, and the contacts separate about 0.6 cycle after the inception of short circuit, the situation is as shown in figure 9. Here curve *a* shows a current wave initially fully displaced, and curve *b* a current wave about 50 per cent displaced, with the minor loop first. While curve *a* gives a higher root-mean-square value of current measured over the full duration, it comes to zero, on account of the decrement, somewhat before a full cycle has elapsed, and runs below curve *b* from 0.65 cycle on. Thus it gives a lower value of ampere-seconds in the arc than curve *b*. The greatest internal pressures were found to be generated in the breaker in cases similar to curve *b*, and, as will be seen in the tabulation of tests given below, care was taken that this particular condition was well represented in the test series.

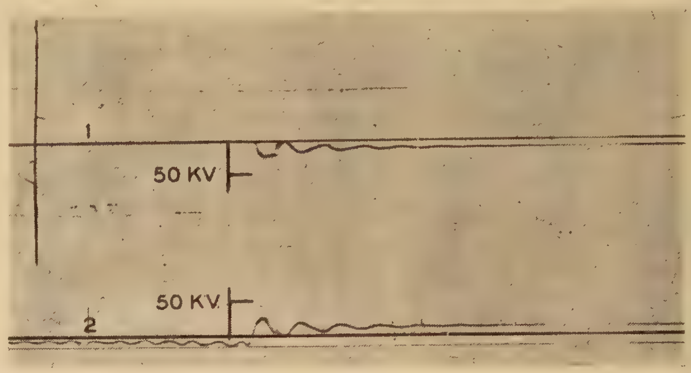

Figure 8. Cathode-ray oscillogram taken with figure 7

Curve 1—Voltage across test circuit breaker

Curve 2—Voltage at transformer side of gap

As railway service is likely to involve more frequent short-circuit operations than either central-station or industrial service, these breakers were built to withstand a large number of short-circuit interruptions and the breaker was subjected to the complete series of tests shown in table I without changing contacts or oil.

In all but one of these tests, the fault was cleared within one cycle after its inception. This exception was one of the light-current tests which started with a minor loop too small to trip the breaker. The breaker tripped on the second loop, however, and cleared the circuit on the third.

Figure 9. Comparison of fully displaced current wave with 50 per cent displaced wave having minor loop first

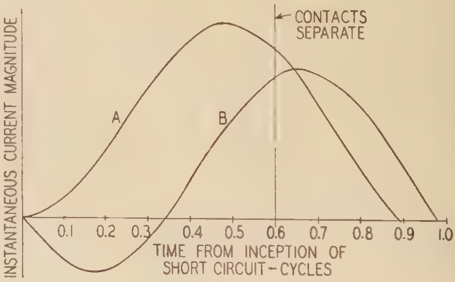

Figure 10 shows the condition of the contacts after test, and it will be noted that the burning is quite moderate for

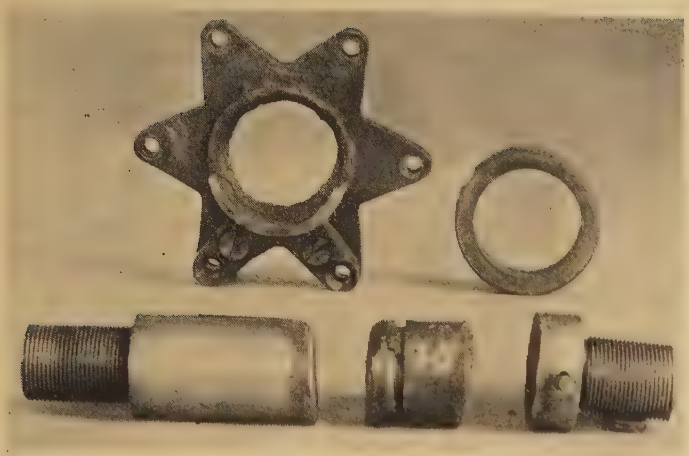

Figure 10. Contacts from impulse oil circuit breaker, 15,000 volts, 1,500 amperes, after test

the large number of severe short circuits interrupted.

Following the short-circuit tests, and without changing the oil or any breaker parts, a high-potential test was applied to the breaker resulting in a breakdown at 49 kv. The path at this breakdown, however, was through a hole which was drilled in the insulating lining to permit pressure measurement during the interrupting-capacity tests and when a sound lining was used together with the oil from the interrupting-capacity tests, the breaker withstood 54 kv for 55 seconds.

Table I. Tests

Number of Tests	Opening or Closing-Opening	Voltage	Current	Testing Circuit	Point on Voltage Wave
10	CO	12,500	3,400– 5,500	Conventional	Random
20	CO	3,000	38,000–70,000	Conventional	Random
10	O	3,000/12,500	36,000–68,000	Special	Equally spaced over 180 degrees
10	O	3,000/12,500	Approx. 40,000	Special	Selected for highest tank pressure
4	O	3,000/12,500	Approx. 67,000	Special	Selected for maximum displacement

After the first high-potential test, a heat run was made on the breaker, using the burned contacts and the dirty oil, with a maximum temperature rise of 28 degrees centigrade.

Conclusions

On the basis of the foregoing, the following conclusions may be drawn:

1. In an exceptionally thorough test program the breaker has shown itself adequate for the severe service for which it is intended, interrupting currents from 3,000 amperes beyond its rating of 65,000 amperes within one cycle, over 50 times without inspection of contacts or change of oil.

2. The testing scheme used, by a four-to-one increase of effective plant capacity, has more than overcome the handicap which the low frequency placed upon the testing plant.

Reference

1. The Impulse High Speed Circuit Breaker, **W. K. Rankin.** *G. E. Review*, volume 34, October 1931, pages 553–8.

Discussion

J. B. MacNeill (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The method of testing oil circuit breakers with a high current at low voltage followed immediately after the interruption by the superposition of high voltage across the open contacts of the switch is questionable, because the conditions in the arc as the current approaches zero are different when this scheme is employed from the conditions that would apply under a circuit giving the same amount of current at the high voltage initially. We are all hoping that ways will be found for improving circuit breakers for large interrupting capacities by the use of relatively small testing equipments, as the handling of switchgear business with a normal cost probably will demand something of this kind for the future. The greatest care must be used, however, to assure reliability of such "synthetic" methods.

A review of past test experience will throw some light on this subject. It is definitely known that test circuits vary in severity and that circuit interrupters which are wholly adequate on some circuits are entirely inadequate on others. The speed of restored voltage and the maximum value to which restored voltage goes are major factors. However, the condition in the arc as the current approaches zero is influenced by the voltage available across the circuit during the interruption and must be given consideration.

Let us look at data taken on the same circuit breaker on two different test laboratories with practically the same applied voltage and approximately the same currents interrupted. Table I shows such a comparison, with the arcing time on the more severe laboratory averaging 3.2 cycles and on the less severe laboratory averaging 2.1 cycles. Again, table II shows a similar comparison on a circuit

Table I. Low-Current Tests

100,000 Kva, 15-Kv Breaker

	Laboratory 1		Laboratory 2			
Test number	35702	35703	2-5807	2-5809	2-5809	2-5810
Voltage	12,000	12,000	13,200	13,200	13,200	13,200
Current (amperes)	830	830	900	900	1,200	1,200
	880	1,060	Three	Three	Three	Three
	870	1,300	Phase	Phase	Phase	Phase
Duration of arcing (cycles)	2.0	2.5	3.0	3.0	3.5	3.5
	2.0	2.0	2.5	3.5	3.5	3.0
	2.0	2.0	3.0	3.5	3.0	3.5
Average current		960		1,050		
Average arcing time		2.1		3.2		

Table II. Medium-Current Tests

	Laboratory 1		Laboratory 2			
Test number	35706	35707	2-5811	2-5812	2-5813	2-5814
Voltage	12,000	12,000	13,200	13,200	13,200	13,200
Current (amperes)	2,870	3,120	2,500	2,500	3,500	3,500
	2,910	2,410	Three	Three	Three	Three
	3,200	3,060	Phase	Phase	Phase	Phase
Duration of arcing (cycles)	2.0	2.0	3.3	3.5	3.0	3.0
	1.5	2.0	3.5	3.5	3.0	3.5
	1.5	2.0	3.5	3.5	3.0	3.5
Average current		2,960			3,000	
Average arcing time		1.8			3.3	

breaker tested in the same two laboratories with the same applied voltage and approximately the same currents interrupted. Here the average arcing time on the more severe laboratory is 3.3 cycles on a 60-cycle circuit and on the less severe laboratory is 1.8 cycles.

These differences in arcing times result in wide differences of arc energy as the last half cycles carry more arc energy and more destructive effects on the contacts and oil. If two laboratories designed for the same specific purpose of circuit breaker testing give such widely different results when operated at the same voltage and applying the same short-circuit current, then we are bound to have reservations on any wide extrapolation such as is caused by testing at a low voltage and superposing across the open contacts a voltage several times as great. If the device under test is good for the given current at the higher voltage, then of course the test method used is of secondary importance. If, on the other hand, there is doubt of the ability of the device to handle the current at the high voltage, very little added assurance is given of the ability of the device by the superposed voltage method.

A preferred method of demonstrating the ability of higher power interrupters is that of dividing the interrupting device into several duplicate parts, each of which can be separately demonstrated to the limit of capacity to which it will be subjected on the complete apparatus. This requires means for assuring proper division of the duty between the several units, but such means have been adequately developed. For the present, however, service requirements do not call for extended subdivision of interrupting devices so that this method also like the one discussed by Mr. Skeats is of limited application.

Any assumption made from tests on 3,000 volts alternating current looking toward verification of higher voltage devices must be carefully reviewed. Three thousand volts alternating current is easy to switch, especially at high current. Under oil a plain break one inch long is adequate. Even in open air certain modifications of standard carbon breakers will do the work. This however, gives no feeling of security regarding 12,000-volt operation, which is a more difficult problem.

W. F. Skeats: Mr. MacNeill presents a table showing considerable difference in the arcing times of the same breaker in tests in different laboratories, claiming this difference as evidence of unreliability of the testing method described in the paper. However, an examination of the differences in testing conditions which might be responsible for this difference in behavior reveals three:

1. A probable difference in the rate of rise of recovery voltage;
2. A difference in the magnitude of recovery voltage as evidenced by the higher test voltage in the second laboratory;
3. A somewhat higher system voltage during the period of current flow.

Of these, items 1 and 2 are admitted by Mr. MacNeill to be of major importance, and they may be well simulated in the testing method described. The third item must derive what effect it has from any distortion introduced into the current wave by the increase in the relative importance of the arc voltage when the system voltage is decreased. In the usual case, this distortion is not great. On the basis of the evidence presented, therefore, it appears that the important differences in Mr. MacNeill's test conditions are those which can be readily taken care of in the test method described in the paper.

Again, Mr. MacNeill points out that 3,000 volts alternating current is easier to switch than 12,000 volts and that any assumption based on tests at the lower voltage must be carefully reviewed before being accepted as valid with reference to performance of the tested device at the higher voltage. This is of course true, but here Mr. MacNeill does not even make the statement that the difference does not lie in the recovery characteristic, which is certainly where it is to be expected and which is simulated by the test method described.

As a matter of fact, a few tests made on an early arrangement of the breaker by the conventional method and also at the same voltage and current, by the scheme described indicate this scheme to be somewhat more severe than the conventional method. This is attributed to the fact that this scheme overemphasizes the increase caused by the arc voltage amplitude of the recovery oscillations.

Printing Telegraph Operation of Way Wires

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Synopsis: Although most commercial telegraph trunk circuits have been operated by printing telegraph methods for some years, Morse operation has been generally adhered to on way wires. Arrangements for operating way wires by printing telegraph have been developed, and are described. These include a polar simplex system, a neutral way-wire system, a code calling bell arrangement, and a multistation customers' printer circuit that provides secrecy by preventing the connection of more than one customer's printer to the line at a time. The paper also describes a new single-line repeater arranged to repeat polar as well as neutral signals, and a "dotter" for transmitting uniform test signals.

COMMERCIAL telegraph messages are transmitted between major cities over a network of trunk lines, usually operated by the multiplex printing telegraph method. These trunks terminate at main "relay offices" of the telegraph company, from which lines radiate to smaller cities and towns. Some of these radiating lines are direct trunks to cities having a considerable amount of traffic, and are equipped with start-stop printers, operated either single or duplex. In other cases, the traffic to a single place is not enough to justify exclusive assignment of a line conductor, and intermediate offices or "way stations" are connected into the circuit to increase the traffic load. Such circuits are called way wires.

The manual or Morse method of operation has been used on these way wires, because of its simplicity and low line-signal frequency and because of the cheapness and ease of adjustment of the apparatus. The way-station operator will usually be the manager of the office, and to provide continuous service a second operator should be available to cover lunch periods and to permit the manager to take care of other business.

The advent of telephone train dispatching and the increasing use of printers on commercial telegraph circuits and on private leased wires has reduced the supply of available Morse operators, so that it is becoming difficult to obtain Morse operators. It is usually better to hire a suitable manager, who can be trained easily and quickly to operate a printer. A messenger can learn in a short time to operate a printer well enough to act as relief operator. It is evident, therefore, that it is desirable in many cases to substitute printer operation of way wires for Morse.

Another use for printing telegraph operation of multistation circuits is for connecting private customers' offices to a telegraph office, where the customers are located at a considerable distance from the telegraph office, but are so placed that they can be connected in series on a single circuit. The total traffic received from all customers may justify the cost of such a line, where it would be uneconomical to provide a separate line to each customer. In such cases, the system must be so arranged that messages to or from any customer cannot be copied by other customers' printers on the same circuit.

Multistation Leased Lines

By "leased line" is meant the type of circuit used for so-called "private wire service," where a subscriber contracts for the exclusive use of a telegraph circuit, over which he transmits and receives his own messages. Multistation leased lines have some points of similarity with the commercial telegraph way wires discussed in this paper, but in other respects their requirements are quite different. A previous paper[1] describes this "private wire service" and points out the fact that the start-stop printer or teletypewriter is particularly suitable for this type of service because of its simple sending, receiving, and timing arrangements, and its automatic ability to take care of varying lags in signals transmitted from any sending station to any receiving station. For the same reasons, the start-stop printer is suitable for way wires.

In many cases the messages sent from any station on these private leased-wire circuits are intended to be recorded at all other stations, as, for example in the case of press or police circuits. In other cases, messages are intended for a particular station and it may be desirable to use a selective calling arrangement. The Gill telegraph selector[2] has been used in some cases for automatically starting and stopping the printer motor at the desired station, when the proper code signal combination is transmitted. This type of selector usually operates on all message signals that pass over the circuit, but it does not close its contacts unless a particular combination of signals is received. This continual operation of the selector mechanism causes wear and maintenance expense. This difficulty has been avoided in other selective calling systems[3] where telephone dials are used to operate step-by-step switches and relays. In these systems, the selective equipment is normally disabled while printing signals are being transmitted and is cut in by slow acting relays when the printers are shut down.

These multistation leased line circuits may extend for long distances, through several telegraph central offices where telegraph repeaters are located, with trained personnel for adjusting them. The individual stations are connected to these central offices over comparatively short loops, which present no severe transmission problems. The cost of the long line circuits and the large volume of traffic transmitted, justify the use of elaborate repeating

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[1] For all numbered references, see list at end of paper.

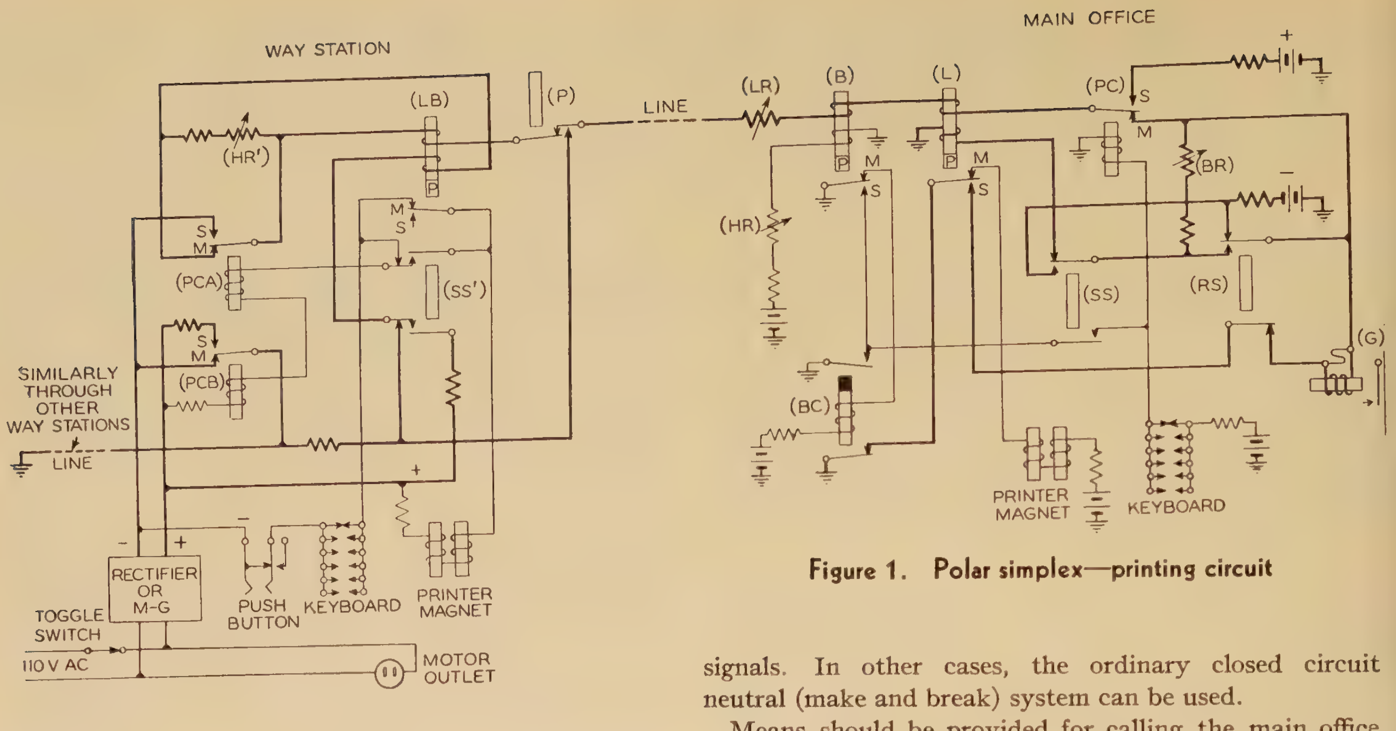


Figure 1. Polar simplex—printing circuit

and selecting equipment, if these are needed to provide good service.

Printer Way-Wire Requirements

The requirements for operating printers over commercial telegraph way wires are quite different from those for operating over private wire multistation lines. These way wires extend from a main telegraph office, through one or more intermediate "way stations," to a terminal office, which may also be considered as a way station. Traffic is exchanged between the main office and each way station, but messages are seldom, if ever, transmitted directly from one way station to another.

The way stations are usually located at a considerable distance from any main telegraph office and skilled attendants are not available for balancing duplex sets or for making any but the most simple adjustments. For these reasons, the way-station apparatus must be simple and reliable. To compare favorably with Morse operation, the cost of the equipment must be kept down, expensive selecting equipment which may require frequent maintenance attention should be avoided, and the power consumption should be reduced to a minimum.

The best wires are not ordinarily assigned to these way-wire circuits. They are usually open-wire ground-return lines and are frequently subject to severe leakage during wet weather and to induced interference from other telegraph circuits or nearby power lines. Start-stop printer signals, at the usual transmitting speed of about 60 words per minute, are approximately twice as fast as the usual Morse signals. For satisfactory printer operation, signal distortion, particularly bias, must be kept below definite limits. These factors impose severe requirements on the system of signal transmission used, and in some cases make it necessary to use polar (+ and −) signals. In other cases, the ordinary closed circuit neutral (make and break) system can be used.

Means should be provided for calling the main office from any way station and for calling any particular way station from the main office, so that the printers can be shut down when not in use. This avoids having messages intended for one way station printed at all other stations, reduces the wear on the printer mechanisms and saves power. A simple code calling arrangement, with single-stroke a-c bells, is being used instead of selectors, so that no d-c supply is required during idle intervals at the way stations, except in a few cases where it is needed at terminal way stations for line current or for operating repeaters.

Polar Simplex System

In this system,[4] polar (+ and −) signals sent from any one station are received by polar relays in series with the line at all other stations, and switching relays are provided for automatically connecting and disconnecting the source of transmitting current to reverse the direction of transmission, so that a station formerly receiving can send back to a station that was formerly transmitting. Any receiving station can "break" or interrupt the sending station, the operation of the printers being exactly the same as on a single closed-circuit line. While sending polar signals from either terminal station, the line is grounded at the other terminal station; and while sending polar signals from an intermediate station, the line is grounded at both terminal stations. Whenever sending stops, the circuit returns to the normal, idle condition, with line current supplied from the main office.

While the circuit is idle, all printer motors can be switched off, as well as the power rectifiers at all way stations. Any way station can call in, operating a signal lamp and buzzer at the main office, and the main office can call any way station by operating a single-stroke bell at each station.

Figure 1 is a simplified diagram of that part of the circuit that is concerned with sending and receiving printer signals. It shows a main office and one way station. The line may extend through several way stations, but as they are identical, only one is shown. Certain parts, such as call bells, signal relays, and the local operating circuits of the switching relays have been omitted from this figure to simplify the drawing.

Negative "marking" battery is normally connected to the line at the main office. When the keyboard is operated, pole changer *PC* transmits (+) spacing and (−) marking signals over the line. Polar line relay *L* responds to these signals and operates the main office printer. Polar relay *LB* at the way station also responds and operates the way station printer. Switching relays *SS* and *RS*, at the main office, operate and remain operated until transmission stops. They have no effect however except to open the biasing winding circuit of relay *L*. Break relay *B* is held by a current through its lower winding equal to about one and one-half times the line current. If the line circuit has considerable capacity, line current surges may operate this relay momentarily at the beginning of each spacing signal, but this will have no effect, as relay *BC* is of the slow-release type and the short circuits momentarily applied by relay *B* to relay *PC* occur at a time when its operating circuit is open at the keyboard.

Signals sent from the way station keyboard operate the printer magnet as well as pole changers *PCA* and *PCB*. Switching relay *SS′* operates during the first spacing signal and remains operated until the way station operator stops sending. It switches the marking contact of *PCA* from ground to the (+) terminal of the rectifier. The rectifier is connected in series with the line and is reversed by the pole changers to transmit polar signals over the line toward the main office and also over the line toward the terminal way station. It should be noted that the direction of current in the line, for marking and spacing signals, respectively, is the same regardless of whether the main office or a way station is sending.

Relay *LB* does not respond to signals from the pole changers at its own station, as marking signals transmitted through both windings in series hold its armature against the marking contact, and spacing signals are sent to line through only one winding while marking current continues through the other winding and is adjusted by rheostat *HR′* to be about one and one-half times the line current. As in the case of relay *B*, relay *LB* may be operated momentarily by spacing current surges due to line capacity. This will open the circuits of the printer magnet and pole changers at a time when they are already open at the keyboard contacts.

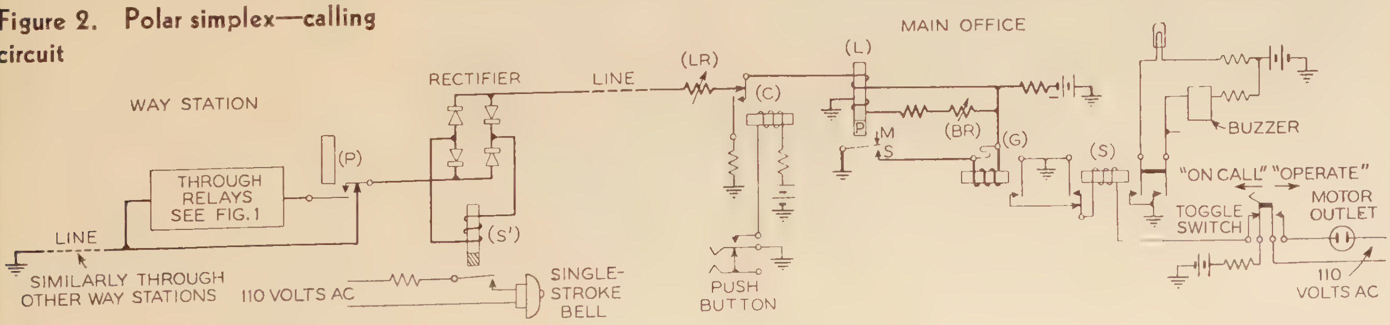
As (−) battery is normally connected to the line at the main office, the first spacing signal from the way station reduces the line current approximately to zero, at first, instead of reversing it. Relay *L* is now operated, however, by biasing current through its lower winding, regulated by rheostat *BR* to be only slightly less than the normal line current. Relay *L* immediately grounds the line through the winding of relay *G*, allowing the line current to reverse. Relay *G* operates switching relay *RS* (over circuits not shown). Relay *RS*, which remains operated as long as relay *L* responds to signals, disconnects the (−) battery from the line and grounds the line through both windings of relay *L*. Relay *L* operates the main office printer magnet causing the printer to record the message being transmitted from the way station.

When the way-station operator stops sending, relay *RS* releases and applies battery to the line at the main office and relay *SS′* releases and disconnects the rectifier from the marking contact of *PCA* at the way station, so that the circuit is automatically restored to its normal idle condition with line current fed only from the main office. Relay *RS* is timed so that it always releases before relay *SS′*, so that marking signal current is always applied to the line at the main office before it is removed at the way station. If the way station operator sends in a slow or hesitant manner, relay *RS* may release occasionally during the message. The momentary double strength marking current will have no bad effect, however, as relay *RS* applies the bias current to relay *L* at the same time.

Relay *P* is operated by direct current from the rectifier. It serves to disconnect the way station printer set from the line when the power is switched off. The arrangement is such that any way station set can be switched on and off without momentarily opening the line or otherwise interfering with other stations that may be using the line.

Any station can interrupt transmission from another station by operating any key on the keyboard several times in succession or by opening the keyboard circuit with a push button "break" key such as that shown at the way station. When a spacing signal from the "breaking" station occurs at the same time as a spacing signal from the transmitting station, the double strength current in the line operates the armatures of the *B* and *LB* relays to their spacing contacts, overcoming the holding currents through rheostats *HR* and *HR′*. Relay *LB* releases pole changers *PCA* and *PCB* as well as the printer magnet. As long as the double-strength current continues, the

Figure 2. Polar simplex—calling circuit



contacts of relay *LB* will remain open and the pole changers and printer magnet will remain released, thus giving a definite indication of the break signal at the way station.

At the main office, relay *L* opens the printer magnet circuit to indicate the break at that station, relay *B* releases relay *BC* and both relays connect a ground through contacts of relay *SS* to short-circuit pole-changer *PC*. The double strength break current continues, therefore, as long as relay *SS* remains operated. When the main office operator stops sending on the keyboard, relay *SS* releases and allows pole changer *PC* to operate and send marking current to the line. This allows relays *B* and *LB* to operate and restore the circuit to normal.

Figure 2 shows the calling-signal arrangement. This apparatus is included in the line circuit of figure 1, but is shown in a separate diagram to simplify the drawings. Slow-release relay *S′* at each way station is connected to the line through a small copper-oxide rectifier so that the line current always flows in the same direction through the relay. This relay remains operated on all printing signals but releases when the line current is stopped by depressing the push button at the main office. The main station can operate the call bells at all way stations, regardless whether the power is turned on the way station sets or not.

To call the main office, the operator at any way station switches on the local power and depresses the push button or any key on the keyboard. Relays *L*, *G*, and *S* respond to operate the buzzer and light the signal lamp at the main office. These signals are released when the main office operator turns on the printer motor to answer the call.

The only operating adjustments required with this system, are the settings of the three rheostats at the main office and the one rheostat at each way station. If properly adjusted, when the circuit is first installed, they usually require no further adjustment, except that, in cases where considerable interference or very heavy leakage is experienced, it may be necessary to readjust bias rheostat *BR*, at the main office, occasionally. The adjustments of break holding rheostats *HR* and *HR′* are not critical, and even if incorrectly adjusted they are not likely to affect the operation of the printers but they may interfere with the proper action of the "break" feature.

The main-office circuit can be arranged so that the circuit can be extended through a concentrator to one of a group of main-office printers or over a duplexed line or carrier circuit to a distant city. The concentrator permits grouping the polar simplex way wire with other lightly loaded circuits and connecting these circuits to the main office printers, only when needed for sending or receiving messages. This reduces the number of main-office printers required and improves the operating efficiency at that office. The extension to a distant city can be used for special purposes such as the transmission of news directly from the way station without rehandling at the main office.

Neutral Way-Wire Printer System

Where line conditions are not too severe, the simpler "neutral way wire" system can be used. This system uses neutral printing signals and reversed current or polar signals for operating the call bells. If the line resistance is not too great, the line may be connected directly to ground at the terminal way station, the line current being supplied from the main office. Positive battery is normally connected to the line at the main office, and for longer lines, a reduced negative voltage can be connected to the line at the terminal way station. As this is of the same polarity as the bell signal potential at the main office, the bell signal current will be reduced to a comparatively low value, normally about 15 milliamperes, but this is sufficient to operate the sensitive polar relay that rings the call bell.

For still longer lines, a single-line repeater can be installed at an intermediate station. A special repeater for this purpose, is shown in figure 3. Ordinary single-line repeaters can repeat neutral or "make and break" signals only. If equipped with fast relays, they can be used to repeat start-stop printer signals. The repeater shown in figure 3, however, is arranged to repeat the polar bell signals as well as the neutral printing signals.

At the main office, the line may be connected permanently to a printer set, if there is enough total traffic to justify it, or it may be connected to a concentrator of either the manual or automatic[5] type. For purposes of illustration, figure 4 shows a neutral way-wire circuit terminated in a manual concentrator at the main office, with an intermediate repeater, with polar bell signal equipment at each way station and with

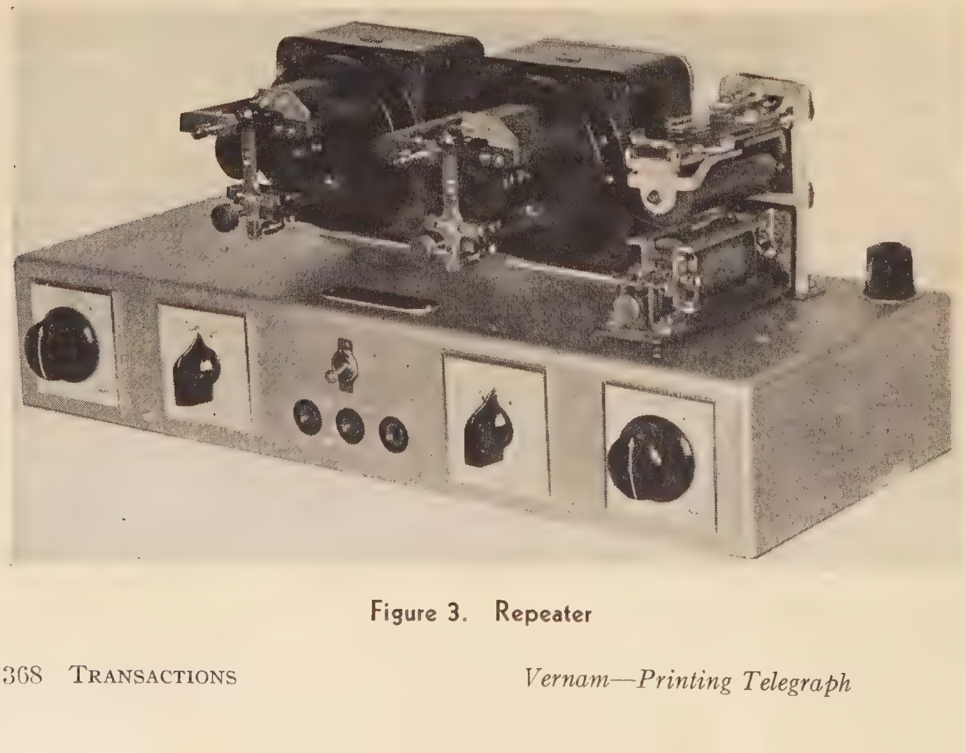


Figure 3. Repeater

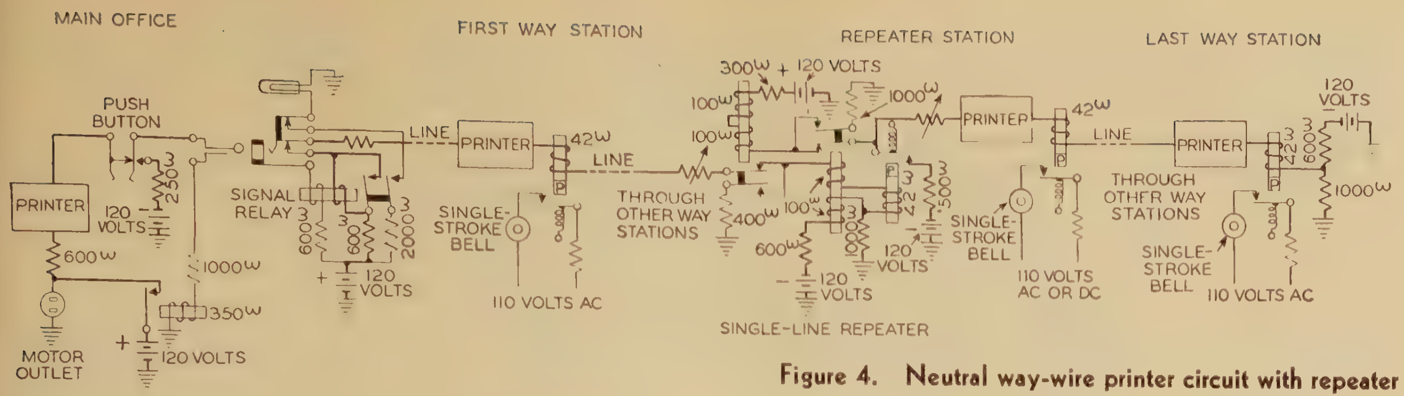


Figure 4. Neutral way-wire printer circuit with repeater

a potentiometer for supplying a reduced line potential at the terminal way station.

High-Speed Neutral Relay

The repeater uses a new fast neutral or nonpolar relay, two of which are shown mounted on the repeater in figure 3. This relay has a laminated core, an aluminum armature lever pivoted on a stainless-steel knife edge, operating two pairs of contact springs. The contacts are of molybdenum, mounted on beryllium copper springs, and are so arranged that they can be adjusted for either break-before-make or make-before-break operation. The latter adjustment is applied, when the relays are used in this repeater. The relay contact springs, and the adjustable spring, are so designed that the increase in spring tension, as the relay operates, closely balances the increase in magnetic pull, as the armature approaches the poles of the magnet core; with the result that the operate and release adjustments of the relay can be brought close together, without adjusting the airgap, as is necessary in the usual type of neutral telegraph relay. Only one simple spring adjustment is required, therefore, to adapt the relay to meet a wide range of operating conditions, including operation over lines subject to considerable leakage. This design and method of adjustment also maintains heavy contact pressures at all times and increases the reliability of the relay.

Single-Line Repeater

Referring to figure 4, with positive battery connected to the line at the main office, the contacts of the polar relays at the repeater and at the way stations are held open by the line current and when the line is opened and closed in transmitting printer signals they are held in the same position by their armature biasing spring. Each of the neutral relays of the repeater responds to printing signals received over one line section and repeats them into the other line section. Each relay also controls a locking circuit for the other relay to prevent it from releasing during the open or spacing intervals in the outgoing signals. As previously explained, the relay contacts are flexible, and are so adjusted that, when the relay releases spacing contact *S* closes before marking contact *M* opens, and when the relay operates, contact *M* closes before contact *S* opens. Therefore, when either relay is repeating signals, the other relay will remain continuously operated, as its circuit always remains closed, either through the *M* contact and line circuit or through the *S* contact and locking resistance. As each relay closes the local locking circuit of the other relay only during spacing signal intervals, the repeater is in condition, during marking signal intervals to transmit a "break" signal from the receiving to the sending station, thus permitting any station to interrupt transmission, if necessary.

During idle periods, any way-station operator can call by depressing his "break" key, momentarily opening the line, releasing the signal relay, and lighting the signal lamp at the main office. The main office operator responds by plugging a printer set cord into the jack and answering on the printer keyboard.

The main-office operator can call any way station by plugging in and depressing the push button the proper number of times. This transmits a reversed current of reduced strength (about 15 milliamperes) over the line operating the call bells at any way stations between the main office and the repeater. Opposing currents now flow through the two windings of the right hand repeating relay, releasing it, and the reversed current operates the polar relay, thus removing the positive potential and connecting a negative potential to the outgoing line and ringing the bells at way stations beyond the repeater.

Referring to figure 3, the single-line repeater consists of a pair of high-speed neutral relays mounted on a base or chassis, together with certain auxiliary equipment. The chassis is an aluminum-finished steel box with a detachable base plate. It contains the resistors, spark killers, rheostats, switches, and jacks and mounts a receptacle for a power-supply plug, a terminal strip for external wiring connections and sub-bases into which the relays are plugged. The polar bell signal relay is mounted on a bracket at the right side of the repeater and there is room for mounting a milliammeter, if required, at the left side. When installed at a way station, this repeater can be mounted on any convenient table or shelf, or if installed at a main office it can be mounted on a standard repeater rack.

A jack is provided in each line for inserting a milliammeter to measure the line current, which can be regulated by a rheostat. The center jack is in a local test circuit used for checking the adjustment of the relays. When the left-hand switch on the repeater chassis is turned to the "cut" position, the "marking" contacts of both repeating

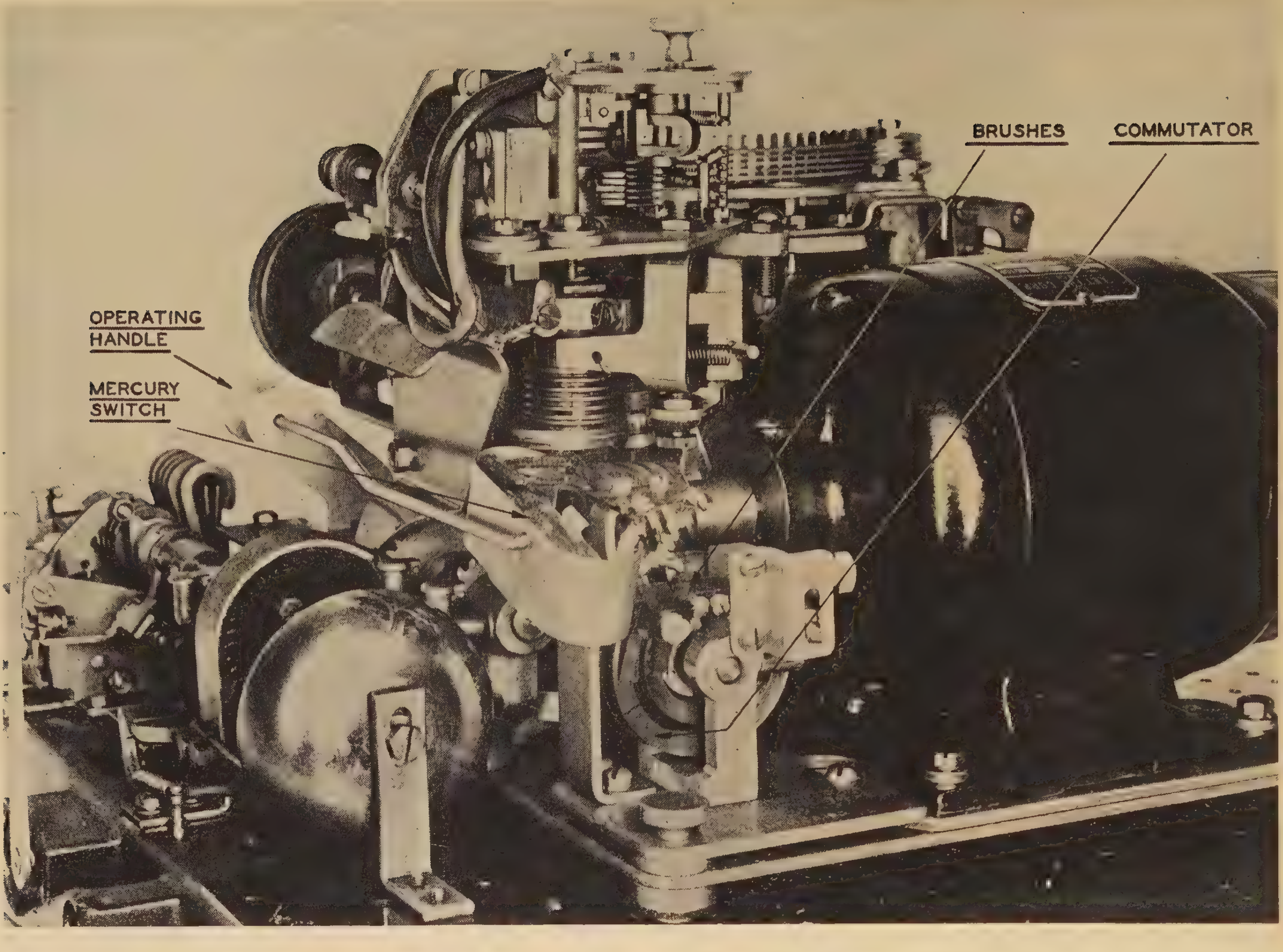


Figure 5. Rear view of printer with dotter attachment

relays are connected in series with this local test circuit. To line up the repeater, the current is measured in this local test circuit and then uniform dot signals are transmitted from an interrupter or "dotter" at the main office. The armature spring of the repeating relay is then adjusted until the milliammeter indicates half the closed-circuit current in the local test circuit. Dotter signals are then sent from the terminal way station to adjust the other repeating relay in the same way. The adjustment should be checked for both wet and dry weather conditions. It has been found that, in most cases, a mean adjustment can be obtained that will operate satisfactorily for long periods without change.

Figure 5 shows a "dotter" that will transmit uniform signals at the same frequency as the printer signals. To reduce its cost, it has been designed as an attachment to a standard tape printer. It consists of a small commutator driven by the printer motor. A link extending to the front of the printer lifts the brushes off the commutator and tilts a mercury switch to short-circuit the dotter when it is not in use.

Figure 6 is an oscillogram illustrating the action of the repeater in repeating printing telegraph signals. The upper curve shows signals as received by the repeater over an artificial open wire line equivalent to 260 miles of number 9 (American Wire Gauge) copper with leakage of one megohm per mile. The signals were transmitted from a "dotter" at a speed of 50 dots per second (100 bauds), which is approximately twice the usual printer signal speed. The lower curve shows the outgoing signals as repeated into a noninductive resistance circuit. It should be noted that, although the windings of one relay are included in the outgoing line, the inductance of the windings does not prevent the outgoing signals from having an approximately square wave shape. This is because the winding always has current through it, as previously explained, and there is no large change in the current through the relay while the other relay is acting to repeat signals. In this particular case, the relay-locking current was slightly greater than the normal line current, and the inductance of the relay winding has an effect opposite to that usually expected. It causes the line current to rise rapidly at the start of each closed circuit signal to a value approximately equal to the locking current. Even if the inductance of another relay or printer magnet is included in the outgoing line, the outgoing signals will more closely approach a square wave shape than if they were transmitted directly into the outgoing line without going through the repeater.

These oscillograms are included solely for the purpose of illustrating the action of the repeater and do not represent the extreme conditions as regards signal speed, etc., under which the repeater can operate.

Two-Wire System With Secrecy Feature

In the previously described systems, the printer can be turned on at any way station to copy messages being transmitted by other stations. This prevents their use for circuits to private customers where privacy is required. To meet the need for a multistation line for connecting customers' printers to a main telegraph office, the circuit shown in figure 7 was developed, and has been used for the last year and a half. As previously mentioned, this arrangement is suitable for cases where the customers' stations are so located that they can be connected in series along a line. It can also be used, to advantage, where customers' stations are located in a group close together but at a considerable distance from the telegraph office.

The number of stations that can be connected on one circuit is limited only by the amount of traffic to be handled. Too many stations should not be connected to one circuit, so as not to delay appreciably any customer's messages. The circuit is normally arranged for a maximum of ten way stations, but could be readily modified to accommodate more.

This circuit requires two wires, which extend from the main office, in series through the way stations to ground. One of these wires, the "control" wire, is used for transmitting calls from the way stations to the main office and for controlling, from the main office, the starting and cutting in of the printer at any particular way station. The second wire, the "printing" wire, is used for transmitting printer signals and for stopping the printer motors and cutting out the way-station printers.

A special form of selector is used at the way stations, consisting of two contacts operated by cams on the shaft of a small self-starting synchronous motor. The motor is somewhat like an ordinary electric clock motor and has reducing gears such that the cam shaft runs at a speed of four rpm. One of the cams is permanently fixed to the shaft, and its contacts serve the purpose of insuring that the motor cam shaft will make a complete revolution after it is started. The second cam is adjustable, and is set at a different position at each way station. Its contact serves to operate the motor-control relay, if the proper signal is received from the main office. A somewhat similar device is used as a sending selector at the main office. This has, in place of the adjustable cam, a distributor or commutator, with one segment for each station to be selected. A manually operated ten-point switch is provided to connect the transmitting circuit to the particular segment corresponding to the desired station.

To call a way station, the main-office operator first sets the ten-point switch to the terminal corresponding to the desired station and then operates the key to the "call" position. This applies positive potential through the main office printer to the printing wire, releasing the "stop" relays and lighting the busy signal lamps at all stations. It also closes a circuit to start the sending selector motor. Immediately after it starts, a cam contact closes, to insure that the shaft will make a complete revolution. When the brush crosses segment *S*, the sending relay is operated momentarily, thus sending a positive impulse over the control wire and momentarily operating the "start" relay and the "selecting" relay at each way station. The start relays start the receiving selectors, and the cam contacts insure that their shafts make a complete revolution. After the start impulse, the sending relay sends negative current to the control wire until the sending selector brush crosses the segment selected by the ten-point switch, when a brief positive impulse is transmitted, momentarily operating the start and selecting relays again.

At the desired station, the contact spring drops into the notch of the adjustable cam while this positive impulse is being received. At this station the motor-control relay operates and locks itself, starting the printer motor and removing a short circuit from the printer. At all other way stations, the adjustable cam is set at a different point, and, therefore, the motor control relays do not operate. At the main office, the control relay operates in series with the sending relay, at this time. It locks itself through the key contacts, starts the printer motor, and opens the starting circuit of the selector motor. After transmitting the positive selecting impulse, the sending relay continues to send negative current over the control wire, as the selector brush continues its revolution to the stopping point.

The milliammeter indicates a slight reduction in current at the instant when the way station printer is cut in. This occurs at the same time as the starting of the main office printer motor, and indicates to the operator that the way station selector has responded properly to the call. Messages can now be transmitted.

It should be noted that the starting of the customer's printer motor is controlled entirely from the main office and that no customer can start his own printer motor or remove the short circuit from his printer magnet. Therefore, only one customer's

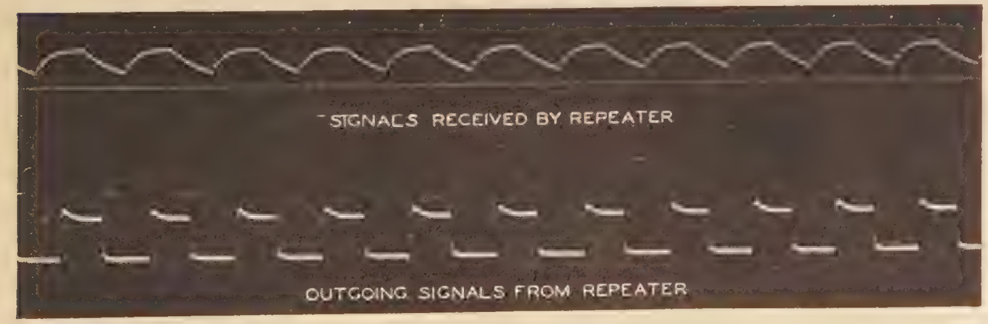


Figure 6. Oscillogram of repeater signals at 50 cycles per second

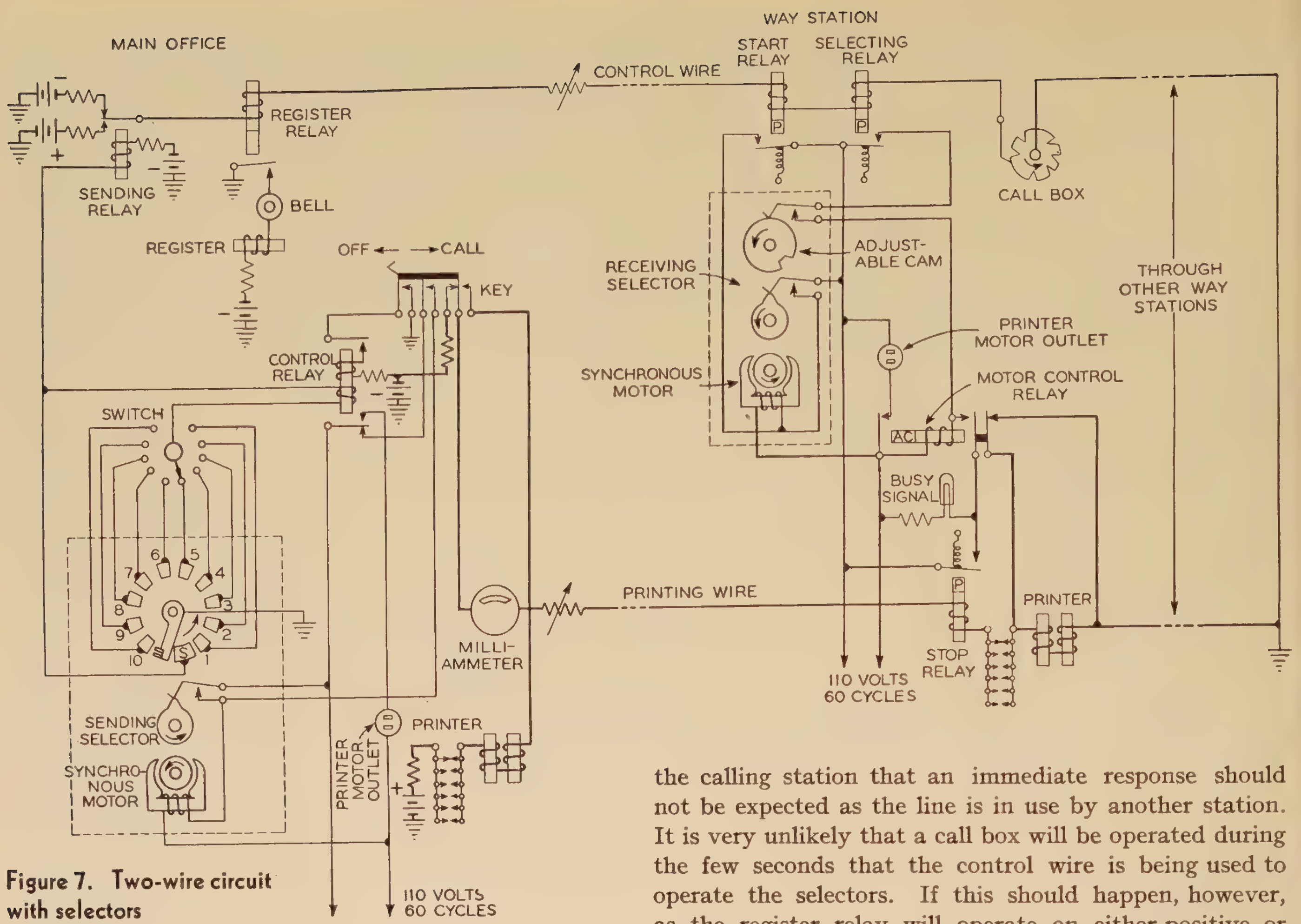


Figure 7. Two-wire circuit with selectors

printer can be connected, in operating condition, to the line at a time and it is impossible for one customer to copy another customer's messages. The control equipment is installed in a locked box to prevent tampering with it.

After the messages have been sent and acknowledged, the operator restores the key, thus releasing the control relay, stopping the main office printer motor, and applying negative potential to the printing wire. This operates the "stop" relays at all way stations, extinguishing the busy lamps and releasing the motor control relay to cut out the previously selected station. The key must be restored to the "off" position, and reoperated, in order to start the sending selector, if another way station is to be called immediately. This prevents the operator from calling a second way station by mistake, without first cutting out the station previously called.

Any way station can call the main office by operating the call box. This is like an ordinary messenger call box and transmits a series of open circuit impulses, different for each station. These impulses operate a single stroke bell and a tape register at the main office, and the signal indicated by the bell and recorded on the tape identifies the particular way station that called. In response to such calls, the main office operator selects and calls this station in the same manner as for sending outgoing messages.

It should be noted that calls can be sent in and registered while the line is busy. The busy signal indicates to the calling station that an immediate response should not be expected as the line is in use by another station. It is very unlikely that a call box will be operated during the few seconds that the control wire is being used to operate the selectors. If this should happen, however, as the register relay will operate on either positive or negative current, and as the call-box signals are much faster than those sent out by the sending selector, such calls will be correctly received and usually will not interfere with the proper operation of the selectors. Even if they should prevent the proper starting of the motor at the called station, the milliammeter will indicate this to the main office operator, who can repeat the call by restoring and reoperating the calling key. In any case, incoming calls cannot cause the selection of a wrong station.

Conclusions

The conversion of way-wire circuits from Morse to printer operation has been retarded by lack of suitable, simple, and reliable equipment for operating such circuits, for calling individual way stations and for preventing one way station from recording messages intended for another. It is expected that the apparatus and systems described in this paper will meet this demand and permit more rapid expansion of printer way wires.

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A New Type Vacuum Seal

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Synopsis: A new type of lead-in structure for vacuum-, gas-, or oil-tight chambers is described in which porcelain bushings are sealed to metal by means of a glass which serves as a bonding agency. The method of assembly is extremely simple, requiring no skilled workmen or elaborate equipment. Some of the features and some of the places where the seal is being applied are discussed.

Introduction

THE PROBLEM of bringing insulated electrical conductors into metal containers which must be hermetically sealed, oil-tight, or vacuum-tight, has for many years been a formidable one. This is attested by the large number of methods now in use, the voluminous literature on the subject and the many patents which have been issued. The most obvious type of lead-in construction is of the gasket type, where a porcelain or glass insulator is used with gaskets between the metal and the porcelain. The whole assembly is held together by some compression arrangement, and the seal depends for its effectiveness upon a tight fit between the metal and gasket, and the ceramic and the gasket. Seals of this type have always been extremely difficult to make perfectly tight. Usually the gasket material, or the structure, is such that it is impossible to heat them to even a few hundred degrees without ruining them. Consequently, it has long been recognized that the most desirable type of lead-in structure is one in which the porcelain, glass, or other ceramic which is used for the insulator, is actually sealed to the metal, either directly or by means of an intermediate sealing material. Seals of this type may be conveniently divided into four classes as follows:

I. Glass or porcelain sealed to metal by means of resins or gums.
II. Glass or porcelain metalized and attached to main metal member by means of low-melting-point metal alloys.
III. Glass sealed directly to metal.
IV. Porcelain sealed to metal by means of a glass.

Seals in class I may be made using ceramics and metals of quite different expansion characteristics due to the plasticity of the resins or gums. They are limited to low temperature applications.

Seals in the second class are usually made between a metal and porcelain which do not match in expansion. The bond is made at the melting point of the alloy and upon cooling to room temperature the structure is quite highly stressed due to the difference in expansion of the components. It is essential that the seals are so designed that all high stresses in the porcelain are compression, as the ceramic materials are very strong for that type of stress.

Seals of this type are mechanically strong and are used extensively, but they are limited to moderate temperatures due to the low melting point of the sealing alloy.

There are many different seals which fall into class III. One of the early seals of this type was made by Housekeeper.[1] At the time this type of seal was developed, available metals, which could be easily worked and glasses were of widely different coefficients of expansion. Under most conditions, if they were fused together at the high temperature necessary to work the glass, the stresses which resulted upon cooling due to the differences in expansion caused the glass to crack. Housekeeper circumvented this difficulty by using a metal which had a low yield point, (copper) and thinning it to a very small section where it sealed into the glass. In this way he caused the metal to flow and prevented the development of further stress in the glass before the stress in the glass reached a high enough value to cause it to crack. One of the main disadvantages of this type of seal, however, is the weakness caused by the thinning of the metal member.

Many advances have been made in the science of sealing metals to glasses, due primarily to the fact that various metals and alloys have been developed which have coefficients of expansion matching those of certain glasses.

One of the greatest and most recent advances in the field is due to H. Scott.[2] From his study of the low expansion anomaly of the iron-nickel-cobalt alloys,[3,4] he found that one particular alloy, which he called Kovar (Patent No. 1,942,260. The alloy Kovar is also known as Fernico. Hull and Burger in a paper[5] on glass-to-metal seals discuss seals to this alloy and many other metals), could be made to match quite closely one of the hard glasses (Corning *G-705-AJ*; Corning code designation for this glass is number 705) from room temperature to above the annealing range of the glass, and can, therefore, be sealed into glass in large sizes. This alloy can be rolled, drawn, and subjected to all the usual forming operations of steel. It is not attacked by mercury and consequently is one of the most important factors in the development of the "all metal" type mercury-vapor thyratrons.

For many types of structures, rather large and intricate glass pieces must be sealed to metal, for which considerable skill is required by the glass worker. It would often be far easier if a porcelain could be substituted for the main body of the glass, and then only a small amount of glass used for bonding the metal to the porcelain. The porcelain will maintain its shape to much higher temperatures

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1. For all numbered references, see list at end of paper.

than the glass and consequently only a minimum amount of skill would be required to make the joint. Seals of this type fall into the fourth class.

The desirability of such a seal has long been recognized and many attempts to obtain a satisfactory one have been made. The successful ones have all been of the "Housekeeper" type.[6] Low-expansion porcelains and glasses having approximately the same coefficient of expansion and which consequently make a stress-free seal to each other have been used. The seal has always been made to a metal of higher coefficient of expansion. In order to prevent cracking of the seal it has been necessary to thin the metal member to a very small section so that the stresses developed would be below the breaking strength of the glass and porcelain. Seals of this type are, therefore, weak where joined.

The new type of seal to be described also falls into the fourth class. The materials have been so selected and the structure so designed that it is no longer necessary to make the "Housekeeper" type seal.

General Principles

The prerequisites for making an ideal seal between metal, glass, and porcelain are:

1. Both the metal and porcelain must be wet by the glass.
2. The metal, glass, and porcelain must all have the same coefficients of expansion up to the temperature where the glass is sufficiently viscous to relieve stresses quickly.
3. All component parts must be vacuum-tight.

A satisfactory seal may be made, even though condition 2 is not exactly fulfilled. It may, therefore, be rewritten as follows: The metal, glass, and porcelain should have coefficients of expansion sufficiently alike that upon cooling after the seal is made the stresses developed due to the differences in thermal contraction are not great enough to cause a fracture of the glass or porcelain, or leave the completed seal mechanically weak.

Wetting

The bonding of glass to metal or what is known as the wetting of the metal by a glass, takes place at elevated temperatures and, in general, only when the metal is oxidized. At the elevated temperature where the glass is viscous and plastic, it dissolves some of the oxide of the metal, and thus adheres tightly to it. In order that the joint between the metal and the glass should be vacuum-tight, the oxide which forms on the metal should be a tightly adherent one. A scaly oxide would naturally give a very weak seal. Care should also be taken as to the thickness of the oxide. If the oxide is too thin, it may all be dissolved by the glass, changing the composition of the glass near the junction, and the resulting glass may not, in fact probably will not, have the same or as great a strength of bonding between itself and the metal as the original oxide of the metal exhibited. A thick oxide on the metal is likely to cause trouble also. In general, a metal and its oxide do not have the same coefficient of expansion, consequently the oxide may develop small fissures or cracks very similar to the cracks in an enameled metal surface when the enamel and metal do not match. In addition, the oxide may be of a spongy nature permitting a slow leakage of air through it.

The wetting of the porcelain by the glass takes place in much the same manner as the wetting of the metal oxide.

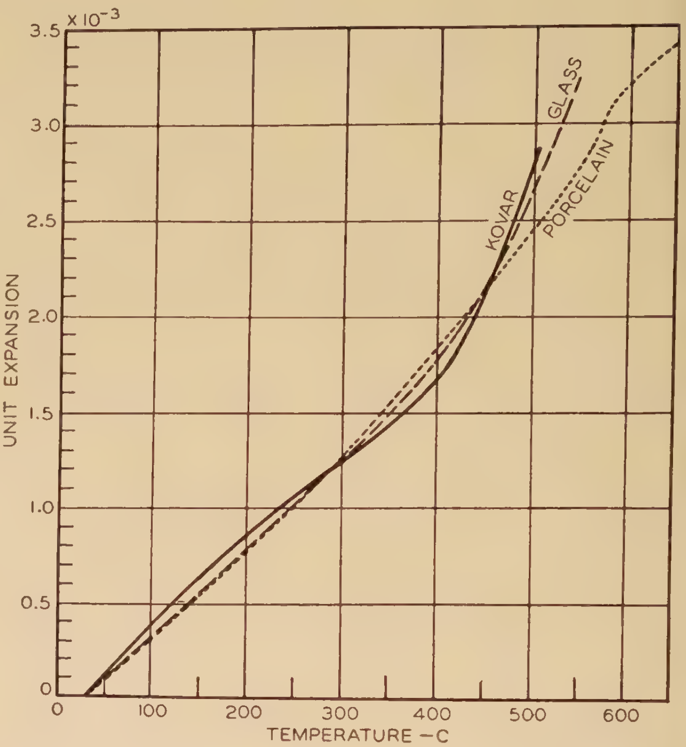


Figure 1. Expansion characteristics of component parts of metal-glass-porcelain seal

The porcelain is already an oxide material, and consequently needs no further oxidation. When the glass and porcelain are heated to a sufficient temperature they tend to diffuse into each other and form a most intimate, tenacious bond which cannot be broken free.

Thermal Expansion

The apparatus used for determining the expansion characteristics of the materials was similar to that used by Scott in his study of iron, nickel, cobalt alloys.[3,4] In order to insure a uniform temperature distribution, a special heating furnace was built which had a large copper core. Thermocouples attached along the specimen showed the maximum variation in temperature to be less than one degree.

Expansion curves were obtained for many different metals, glasses, and porcelains, but for the purpose of this paper, only one particular combination will be discussed. The materials are, the iron-cobalt-nickel-alloy, known as Kovar, the glass *G-705-BA* (Corning code designation for this glass is number 704), and standard electrical porcelain. As will be shown, these materials all have approximately the same expansion characteristic over a considerable range, and can be satisfactorily sealed together. Although there are other combinations of metals, glasses, and porcelains which also meet the requirements of a satisfactory seal, these particular ones have been chosen because of their availability. All components are standard materials and are readily obtainable. Figure 1 gives the total thermal expansion per unit length of the materials as a function of the temperature. They are shown together for comparison, and as may be seen they have very nearly the same average coefficient of expansion up to about 500 degrees centigrade.

Relief of Stresses

In order to show that a stress-free seal can be made between Kovar and electrical porcelain, it is necessary to show that *G-705-BA* glass has a low enough viscosity at a temperature around 500 degrees centigrade to permit the Kovar and porcelain members to move with respect to each other at a rate sufficient to compensate in a reasonable time for the difference in expansion between the Kovar and porcelain at temperatures above 500 degrees centigrade. If, then, all stress is relieved at around this temperature, no appreciable further stress will be developed upon cooling to room temperature, as all components contract practically the same amount.

There are two particular temperatures defined in glass technology which are of importance in connection with relief of stresses in the glass. These are known as the *anneal point*, and the *strain point*. The anneal point is that temperature at which 90 per cent of the stress in the glass will be relieved in 15 minutes. The strain point is that temperature at which the same percentage will be relieved in four hours. The range between these temperatures is usually spoken of as the annealing range. The Corning Glass Works, in published data on their commercial glasses, gives these temperatures. For *G-705-BA* glass they are 484 degrees centigrade and 450 degrees centigrade for the anneal point and strain point, respectively.

It would seem that, if a metal-glass-porcelain seal were made, and, before cooling, held at around 484 degrees for 15 minutes or longer, most of the stress would be relieved. That this is not true will be shown.

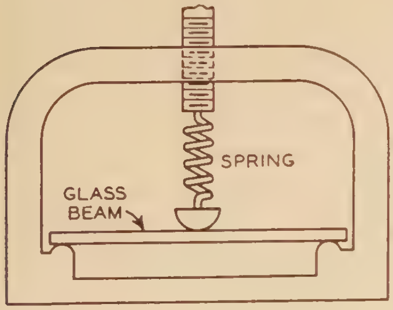


Figure 2. Glass beam loaded by means of a device having considerable elastic deformation

There are a number of methods which have been used for determining the annealing constants of glass, but only one method[7] which clearly shows the implications of these data will be described here. A small rectangular plate of the glass to be studied is supported at opposite ends, and stressed by tightening down a screw in the center between the two supports. The loading mechanism is made very rigid so that no appreciable elastic deformation will take place, and so that the glass will be permanently constrained to a fixed position. This is all set up inside a uniform temperature furnace and so arranged that light can be directed through the specimen, and relief of stresses determined directly for any particular temperature by a photoelastic method. Thus the two temperatures are found which satisfy the definition of the anneal point and strain point.

Further study has shown that these temperatures correspond to points where the glass has definite values of viscosity,[8] and that the rate of relief of stresses may be found if the viscosity is known. It was then experimentally determined that the common logarithms of the viscosity measured in poises at the anneal and strain points are 13.4 and 14.6, respectively. Since the determination of viscosity from a study of the mobility of glass fibers is a much simpler method of finding the anneal and strain points, it has almost completely supplanted the older, more direct methods. However, we must still remember that, no matter how these temperatures for rates of annealing are determined, they apply directly only to the case where the glass is constrained to some definite shape, and the stress is relieved while the glass remains in that position.

Consider a glass beam which instead of being loaded by a rigid screw is stressed through a stiff elastic spring similar to that shown in figure 2. If this is held at an elevated temperature, say the anneal point, the stress in the glass will tend to be relieved. However, as the stress in the glass is relieved, it will be still farther strained due to the elasticity of the spring. Consequently the stress in the glass cannot be completely relieved until it has deformed so far that it has permitted the elastic deformation of the spring to be completely relieved. It is at once apparent, therefore, that the annealing of a glass structure constrained by an elastically deformable means, will be greatly dependent upon the rigidity of this mechanism.

In the construction of metal-glass seals, the elastic deformation of the metal may be a very important consideration in determining the rate of relief of stress in the glass. For a simple bead seal, where a layer of glass is melted around a quite rigid metal rod, the deformation of the rod is negligible under the stresses produced. It is, therefore, substantially correct to assume that, at the annealing temperature, 90 per cent of the stresses due to any differences in expansion between the metal and the glass will be relieved in 15 minutes. It is incorrect, however, to assume that an annealing schedule which is correct for a bead on a heavy rod will be satisfactory for all other shapes of seals. Thus, for example, a bead of the same size made on a thin wall tube having the same outside diameter as the solid rod, will anneal quite differently. The initial stresses will be lower due to the fact that the metal deforms elastically, but the rate of relief of stresses will also be slower. It can be shown that after a time t the stress in the glass on the metal tube, may actually be higher than in the glass on the solid rod, even though the initial stresses on the rod seal were higher. This is due to the fact that the rate of relief of stress is lower for the seal on the metal tube. A graphic illustration of stress versus time is shown in figure 3.

In order to have the same rate of relief of stress for the tube seal as for the rod seal, it is necessary that the viscosity of the glass should be lower. In consequence the temperature of annealing would have to be higher. It may be seen, therefore, that it is desirable to have the metal and glass match up to temperatures above the so-called annealing point of the glass.

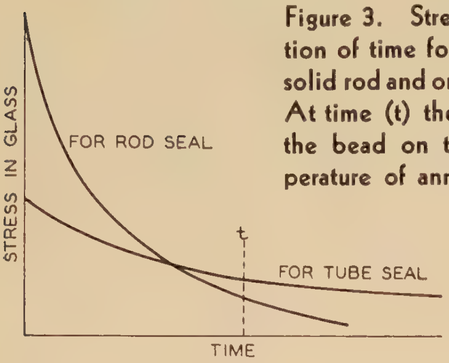


Figure 3. Stress in glass as a function of time for a bead seal on a solid rod and on a thin-walled tube. At time (t) the stress is higher in the bead on the tube. The temperature of anneal is the same for both seals

Since Kovar and *G-705-BA* glass match quite closely even at temperatures well above the anneal point, little difficulty is encountered in obtaining a satisfactory anneal in a short time for most any type of structure.

For a seal between Kovar, glass, and porcelain, conditions are somewhat different. Let us consider the case of a moderately thick-walled tube of Kovar sealed to a porcelain tube with a thickness a of glass between them, as shown in figure 4. The seal is made at a high temperature (usually between 900 degrees centigrade and 1,100 degrees centigrade, depending upon the design), and consequently the Kovar and glass have expanded considerably more than the porcelain. After the seal is made and cooling is started, the metal tends to contract faster than the porcelain, and consequently stresses are set up in the seal. In order that these stresses may be relieved at the lower temperature, the glass must permit the metal to move with respect to the porcelain by an amount equal to the difference in contraction between the metal and porcelain in cooling from the temperature at which the seal is made to the lower temperature. As soon as this relative motion of the parts is required during the annealing process, we see that the anneal point of the glass no longer defines the temperature at which 90 per cent of the stress will be relieved in 15 minutes. Either a higher temperature is necessary, or a longer time will be required.

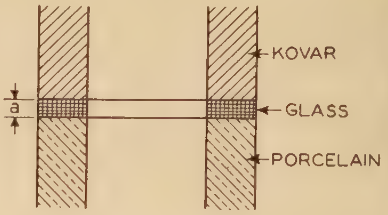
Now it is known that the rate of flow with respect to each other of two surfaces in shear and separated by a viscous medium is proportional to the distance of separation (a for our case) and inversely proportional to the viscosity. Consequently the greater the thickness of the glass, the faster the relief of stresses for a given temperature.

If a seal is made using a thin layer of glass, and is cooled quite slowly, the stresses developed are so high that they usually crack the porcelain.

Figure 5 shows another way in which Kovar and porcelain might be sealed together by means of glass.

After the seal is completed and cooling started, the metal tends to shrink down on the porcelain. Now in order that the resulting stresses may be relieved, the glass must be squeezed out somewhat so that the metal can move toward the porcelain. This is analogous to a long thin strip of viscous material in compression between two plates. Doctor Nadai has shown (this is from an unpublished Westinghouse research report entitled "The Distribution of the Pressure in Thin Layers of Viscous Material Under Compression," by A. Nadai) that for this case, the velocity with which the plates move together is approximately proportional to $\frac{1}{\eta}\left(\frac{a}{l}\right)^3$ where η is the coefficient of viscosity. It is, therefore, important that the ratio l/a should not be large. For the case of the long thin strip in compression, the pressure distribution is not constant along the dimension. It has been shown that it takes on a somewhat parabolic shape, dropping very low at the edges. This is advantageous, as it tends to cut down the danger of stress concentration at the edge of the seal which might break the porcelain.

Figure 4. Kovar and porcelain sealed together by means of a thickness of glass (a)



Calculations, of the rate of relief of stress for several simple structures, have been made, but exact solutions even in the simple cases, were found quite impossible due to the complexity of the mathematics involved. The approximate solutions indicated, however, that the range of temperature, in which the greater part of the stresses developed upon cooling from a higher temperature can be relieved in a moderate length of time, is around 100 degrees centigrade higher than the so-called annealing range of the glass. Any seal annealed at this temperature will, however, develop further stresses upon cooling down the next 100 degrees, due to the difference in expansion of the components above 500 degrees centigrade. It is, therefore, necessary that the design be such that the principle residual stresses in the glass and porcelain are compression, as both are many times stronger in compression than in tension. Care should also be taken to avoid stress concentrations which might cause cracking of the glass or porcelain.

Another factor which undoubtedly enters into the relief of the stresses in seals annealed at high temperature is the relaxation in the Kovar. Scott has shown[2] that at temperatures as low as 400 degrees centigrade, Kovar loses 50 per cent of the maximum stress applied by bending, in 15 hours. At the higher temperatures, this takes place at a much greater rate, although no specific data are available.

Any types of seal which might be made between metal, glass, and porcelain are modifications or combinations of the structures in figures 4 and 5. Consequently, from the foregoing analysis of annealing of seals, it may be seen that *it is quite impossible to obtain complete relief of stress in a metal-glass-porcelain seal in any reasonable length of time. It has also been shown that the rate of relief of stresses in metal-glass seals, and in metal-glass-porcelain seals is a function of the design constants of the structure, as well as the viscosity of the glass and relaxation characteristics of the metal.* Rough analysis and experimental verification show that by so adjusting the seal design that stress relief will continue to as low a temperature as practically feasible, a satisfactory strong seal can be made.

Vacuum Tightness of Components

Finally, in order to have a good seal it is necessary that all components of the structure, and the joints between them be vacuum-tight. Nothing further need be said about Kovar and glass, for their extensive use in the metal radio tubes, metal thyratrons, etc., speaks for them. Tests made on many types of porcelain show that all those that are well vitrified are vacuum-tight, and that a vacuum-tight seal between them and a glass of the proper expansion may easily be made. The tests were made by closing off one end of a tubular porcelain structure and sealing an ionization gauge onto the other end, after which the whole structure was baked and treated under vacuum and then tipped off. Gauge readings were then taken from time to time to see if there was any leakage. No pressure change has been detected in seals made over a year and a half ago.

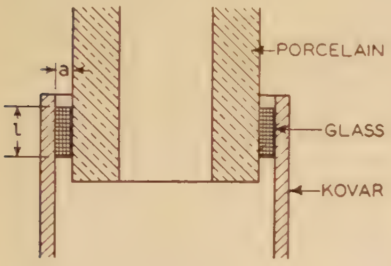


Figure 5. Kovar and porcelain sealed together by means of a thickness of glass (a) and length (l)

Tests made in a somewhat similar manner on completed metal-glass-porcelain seals show them to be vacuum-tight.

Assembly of Seals

Metal-glass-porcelain seals may be assembled in a number of ways. One of the most obvious ways is the utilization of the usual glass blowing technique. The porcelain member is brought up to temperature slowly and when it is sufficiently hot a glass bead is worked upon it at the point where the seal is to be made. The Kovar portion is then heated to a dull red heat for a few seconds to give it a slight oxidation and sealed to the glass.

For commercial production, such a method is too slow and expensive. A method is desirable by which larger quantities can be made at one time and without the assistance of skilled workmen. Such a method will now be described, as applied to the assembly of terminals for oil-filled capacitors.

Figure 6 is a photograph of the components of one of the terminals. The Kovar cap and flange, parts *A* and *E*, respectively, are drawn from sheet material, and the glass rings *B* and *D* are cut from a standard-gauge tubing. The parts are stacked together on a vertical spindle of heat-resisting steel and are ready for the furnace.

The sealing cycle depends upon the size of the porcelain pieces, and whether a batch or a conveyor type furnace is to be used. The final seal is made in the temperature range 950–1,100 degrees centigrade. If the porcelains are quite small it is sometimes possible to put them directly into the furnace at this temperature, although in general this will not be the case. Porcelain is a very poor conductor of heat, and the resulting high thermal gradient and consequent high stress is usually sufficient to crack the porcelain. Rapid heating is especially bad for the porcelain in the temperature range from about 500 to 575 degrees, where the expansion shows a marked increase. Consequently it is usually found advisable in batch assembly of small terminals to preheat, holding the furnace temperature slightly above this dangerous zone (about 600 degrees centigrade). As the porcelains come up to temperature their rate of heating becomes less and less and they are carried through the dangerous zone without cracking.

Above this temperature the expansion coefficient is lower, and the porcelain will stand higher thermal gradients. The assembly may, therefore, be transferred directly from the preheat furnace to the sealing furnace, which is at a temperature of around 1,100 degrees centigrade. Except for very small terminals which can be heated rapidly it is usually desirable to have the sealing operation take place in an oxygen-poor atmosphere in order to prevent overoxidation of the Kovar. An atmosphere of tank nitrogen is satisfactory.

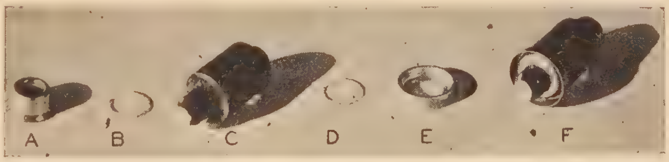


Figure 6. Component parts of a metal-glass-porcelain terminal seal and a completed terminal

A—Kovar cap B and D—Glass rings C—Porcelain
E—Kovar flange F—Completed terminal

After the seal is made the terminal should again be brought to an intermediate temperature furnace at around 600 degrees centigrade. It is during the interval of cooling to this temperature, and while at this temperature, that the major portion of the annealing takes place.

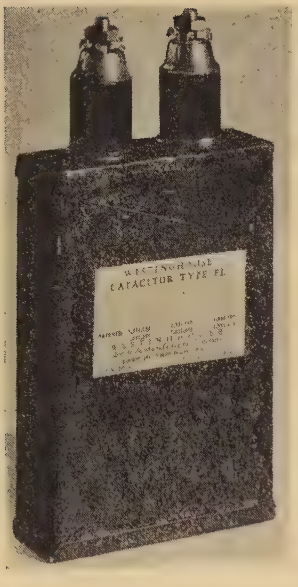


Figure 7. Inerteen-filled capacitor using two metal-glass-porcelain terminals

It also may be desirable to maintain a hydrogen atmosphere in this furnace in order to reduce the surface oxides on the exposed Kovar surfaces.

The terminals are next moved to a cooler zone in the furnace and after they reach a temperature around 300 degrees centigrade where no appreciable oxidation of the Kovar will take place, may be removed from the furnace.

It has been found possible to use the same furnace for both the preheating and for the cooling and annealing. Figure 6*F* is a completed terminal which was assembled using the following cycle: seven minutes, preheating; 15 minutes, sealing; and 20 minutes, cooling and annealing. The correct cycle to be used is largely a matter of size and shape of the porcelain and may best be determined by experiment. If the quantity is sufficient to warrant it, a seal of this type is admirably suited to production in a continuous-type furnace.

Applications

When work was started on the development of metal-glass-porcelain seals, it was intended primarily for application to vacuum-type equipment. It soon became apparent, however, that the demand for oil-tight and gas- and vapor-tight terminals was greater, as the needs of those using vacuum containers were quite well met by metal-glass seals. It is in consequence of the relative demand, that the first designs of the metal-glass-porcelain seal were for use on oil-filled capacitors.

Figure 7 shows an Inerteen-filled capacitor using two metal-glass-porcelain terminals of the type just described. The terminals are soldered into the can and the leads from the capacitor brought out through the opening in the caps. These are soldered to the caps at the same time the threaded studs are soldered in. Terminals for capacitors are standard in three different sizes, and others are being used experimentally. The same terminals are being considered for other applications such as small oil-filled transformers, and oil-filled portable X-ray equipment. They have a distinct advantage over other types, in that they permit bringing the leads out of the container below the oil level.

The possible uses of a seal of this type are so many and varied that it would be impossible for me to enumerate them. In fact, it may be used practically any place where an electrical lead into a hermetically-sealed container is desired. The individual reader will undoubtedly be able to select from his own experience many places where it might be applied.

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A Stabilized Amplifier for Measurement Purposes

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Synopsis: This paper describes a stabilized amplifier with an over-all amplification ratio that remains essentially constant in magnitude and phase for all changes in tube characteristics, line-voltage variations, and output load variations to be expected during normal operation. This stability is obtained by the introduction of two stabilizing circuits which act independently, yet are complementary when used together. During a period of eight weeks' use two such amplifiers with their associated indicating instruments maintained their original calibration within two-tenths per cent of full scale without readjustment.

Introduction

DUE TO ADVANCES in electron tubes and amplifier technique electronic devices have found a rapidly expanding field of application. They have been used quite extensively in measurements and with the aid of amplifiers[1] it is possible to measure smaller quantities than ever before. Such quantities as voltage, current, time, sound, light, and distance can be measured and, moreover, the measurement can be made without appreciably disturbing the circuit characteristics by the introduction of the measuring device.

However, past experience has indicated that when an ordinary amplifier is used to extend the sensitivity of an indicating instrument, such as a voltmeter or ammeter, the accuracy, reliability, and ease of operation of the amplifier do not begin to approach those of the indicating instrument. Although the electron-tube amplifier has remarkably linear properties, variations in tube characteristics between different tubes, with the age of tubes, and with changes in plate voltage and cathode temperature ordinarily cause the over-all amplifier characteristics to change from time to time. Accuracies in the order of one-half per cent are available in present-day instruments and if the over-all amplifier characteristics are not to extend this limit it is necessary either to control the variables during operation or else provide means for a special calibration to check each reading. Either method is inconvenient from the operator's viewpoint and in many cases the resulting uncertainty in measurement does not permit the use of such an amplifier. Either special instruments are built or special ways of using instruments are devised.

In such applications where accuracy and reliability are important, together with sensitivity, it is desirable to have an amplifier whose characteristics are essentially independent of the aforementioned variables.

Specifications

One of the major problems encountered during the recent design of a 480-cycle network analyzer[2] was the measurement and instrument system. A network analyzer consists essentially of a large number of variable circuit parameters conveniently arranged for interconnection such that various circuit problems which are too complicated or involved for direct mathematical calculation may be set up in miniature and the actual results measured by trial (volts, amperes, watts, phase angle, etc.). Such analyzers are used primarily in making load and stability studies of power systems, but the circuits are flexible enough so they can be used for a great variety of problems.

For such an analyzer it is desirable to have instruments that are: easy to read without undue eye strain up to distances of several feet, rapid in response, able to withstand overloads and abuse, easy to use, and accurate to one-half per cent with direct-reading scales. Now these requirements alone would not preclude the direct use of indicating instruments, but it is also necessary to reduce the disturbance caused by inserting the instruments into the network to a point where it can practically always be neglected even when the network is lightly loaded. In an effort to reduce the size, weight, and cost of this analyzer, the power consumption of the total network is made small. Thus, the allowable instrument power consumption is reduced to such a small value that it is hopeless to attempt to use directly any kind of an indicating instrument even if some of the other desirable characteristics are sacrificed. For instance, it is desirable to have an ammeter voltage drop that is not in excess of 0.010 volt with various full-scale currents of 0.010–0.050–0.250–1.000 ampere. The voltmeter should not require over 0.000150 ampere (150 microamperes) when measuring full-scale voltages of 15–30–75–150 volts. Having given these specifications for sensitivity, the primary considerations are accuracy and reliability.

In the network-analyzer application current is measured by inserting a low-resistance shunt into the circuit and then amplifying the voltage drop across this shunt. The amplifier input impedance in parallel with this resistance is made high enough so it may be neglected. For instance, the current amplifier input impedance is not less than 5,000 ohms (maximum resistance of shunts is one ohm) and with the full-scale voltage drop of 0.010 volt the amplifier input is some 0.000002 ampere (two microamperes). This input corresponds to an amplifier output of 0.100 ampere so the current amplification is about 50,000.

Voltage is measured by using a tapped high-resistance voltage divider, each tap having sufficient resistance to

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[1] For all numbered references, see list at end of paper.

limit the current to 0.000150 ampere at the desired full-scale voltage. The voltage drop across a 3,000-ohm portion of the divider is amplified for an indication. The amplifier input impedance is not less than one megohm, which at full scale requires about 0.00000045 ampere (0.45 microampere). This input corresponds to an amplifier output of 0.050 ampere, the over-all current amplification being about 100,000. However, while the actual amplifier input is in the order of 0.1 microvolt-ampere; the relative disturbance caused in any circuit by the introduction of these amplifiers for making measurements must be measured by the over-all volt-ampere requirements of the complete unit and not the amplifiers alone. In this case, the volt-ampere requirement of the resistance shunt is predominant. A current of 0.010 ampere is measured with 0.010-volt drop and a voltage of about 0.5 volt can be measured with a current of 0.00015 ampere; about 0.0001 volt-ampere (100 microvolt-amperes) being required for full scale in each case.

To get a better conception of the meaning of these figures consider table I and compare the volt-ampere requirements of those high-quality a-c instruments in common use with that required in the network-analyzer instruments. The instrument voltage and current ratings given were chosen as typical values that might be expected of an average quality portable instrument in general use. The ammeter voltage drops were derived from the instrument impedance and current ratings and the voltmeter current requirements were derived from the impedance and voltage ratings. The volt-ampere requirements give an approximate idea of the relative disturbance caused when that type of an instrument is introduced into a circuit. To further facilitate this comparison a column is included in which the volt-ampere requirements are expressed in relative values considering the new ammeter value as unity. For convenience in comparison the wattmeter potential- and current-element volt-amperes are added together.

Table I. Volt-Ampere Requirements at 480 Cycles of Representative 60-Cycle Instruments Compared With New Amplifier Type

Instrument	Characteristics at 480 Cycles: Volts	Amperes	Volt-Amperes	Ratio to Amplifier Type
Ammeter				
Electrodynamic	2	5	10	100,000
Moving Iron	1	5	5	50,000
Thermocouple	0.25	0.05	0.012	120
Rectifier	2	0.01	0.02	250
Amplifier	0.01	0.01	0.0001	1
Voltmeter				
Electrodynamic	150	0.07	10	100,000
Thermocouple	1	0.001	0.001	10
Rectifier	1	0.0005	0.0005	5
Amplifier	0.7	0.00015	0.0001	1
Wattmeter*				
Electrodynamic				
Current	1.5	5	7.5	
Potential	100	0.02	2	
			9.5	95,000
Amplifier				
Current	0.01	0.01	0.0001	
Potential	0.7	0.00015	0.0001	
			0.0002	2

* Volt-amperes of potential and current elements combined for convenience.

Of those instruments listed the electrodynamic and the moving iron are probably in greatest general use because of their high accuracy and reliability, but note that they require the largest volt-ampere input for operation. Also, due to the increase in reactance drop at higher frequencies, the volt-ampere requirements and errors increase quite materially. Particularly does the wattmeter accuracy suffer at higher frequencies because of various phase shifts and mutual effects in the windings. This is especially important in this application because the wattmeter must maintain its accuracy even at very low power factors; a requirement exceedingly difficult to obtain even at 60 cycles. So these volt-ampere requirements tell but a small part of the difficulties encountered in building a wattmeter. A conventional thermocouple instrument is useful even at very high frequencies but is extremely slow in response and quite easily burned out with overloads. Descriptions of thermocouple wattmeters have been published but such wattmeters are not in general use. The accuracy of the rectifier type of instrument is not high enough for this application and the wattmeter is not commercially available.

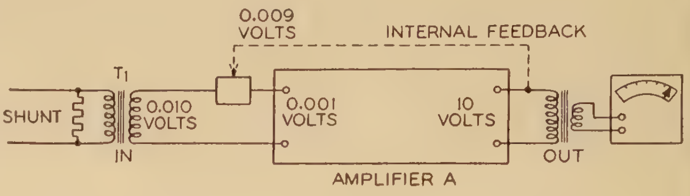

Figure 1. Internal feed-back circuit

So, after giving due consideration to the various instrument characteristics, it is apparent that to satisfy the requirements of speed, accuracy, reliability, low burden, etc., it is advisable to use the electrodynamic or moving-iron type of instrument either of which is suitable on every score except sensitivity, and then supply this sensitivity with an amplifier. Of course, the amplifier must be as reliable in every way as a high-quality indicating instrument. The input-output ratio and phase angle must remain constant within one-half per cent for all changes in tube characteristics, plate voltages, etc., to be expected during operation. Also, as it has turned out, the amplifiers must be able to correct some of the inherent inaccuracies found in a moving-coil-type wattmeter.

Description

The over-all amplifier input-output ratio is made essentially independent of most changes that occur within the amplifier by introducing two stabilizing feedbacks. Each acts independently yet they have a compounding effect when used simultaneously. The specific amplifier referred to in the text is designed only for a frequency of 480 cycles (±2 per cent); however, with suitable modifications the feed-back principles described can be applied to other single-frequency or broad-band amplifiers.

In the first stabilizing scheme, an internal feedback similar to that used by H. S. Black[3] and associates, the amplifier is deliberately built with several times the necessary amplification, and then, by feeding a portion of the output back on the input in such a way as to throw away the excess amplification, the amplifier will acquire new properties, the most important of which is constancy of amplification and freedom from nonlinearity.

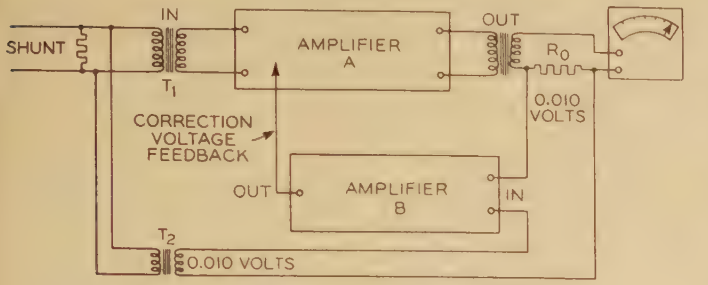

Figure 2. Null-balance feed-back circuit

The principle of such an amplifier can be explained quite readily by considering a specific example. Assume, as shown in figure 1, that 0.010 volt is available as amplifier input to give a ten-volt output. *A* represents an amplifier that delivers ten volts output with 0.001-volt input, but instead of using it as an ordinary amplifier part of the output voltage, namely, 0.009 volt, is introduced back into the input circuit such that the amplifier input of 0.001 volt represents the difference between the feed-back voltage of 0.009 volt and the impressed voltage of 0.010 volt. Amplifiers are subject to normal variations in the order of ten per cent so assume that for some reason or other the amplifier in question should change and now require an input of 0.0011 volt instead of 0.0010 volt, an increase of ten per cent. The output voltage remaining constant, the feed-back voltage will be 0.009 volt. Adding to this the new amplifier input of 0.0011 volt, the total input required is now 0.0101 volt instead of 0.010 volt as before. This represents an increase of one per cent in input volts corresponding to an error of ten per cent in the amplifier ratio, so with a feedback of ten times, the errors are reduced to one-tenth. By increasing the amplification and increasing the feedback, the error can be reduced still further, until a point is reached where the feedback is so large that the over-all amplification characteristics are substantially unaffected by most changes in the amplifier. It is far from a simple proposition to employ feedback this way because of the tendency for oscillation and the very special control which is required of phase shifts in the amplifier and feed-back circuits over a wide range of frequencies above and below the useful frequency band. However, once having achieved a design in which proper phase relations are secured the performance obtained is perfectly reliable.

When adjusted properly this scheme exerts a remarkably stabilizing effect on the amplifier but a second means for obtaining stability is used which serves as a check on the first. This second means consists of an external feedback, which is so-called because it is external to amplifier *A* and which is nothing more or less than a special use of the familiar and extremely accurate null-balance system. As shown in figure 2, a resistance R_0 is introduced in the output circuit of such value that 0.010 volt appears across it with the proper full-scale current flowing through the indicating instrument. This voltage is then compared with the input voltage of 0.010 volt and they should be identical. However, should either one increase or decrease more than the other or change phase angle with respect to the other there will be a voltage difference. This difference, or error as it is in this case, can then be amplified by an amplifier such as *B* and introduced directly back into amplifier *A* in such manner that it will adjust the output of *A* to the correct value corresponding to the input voltage.

There is another advantage in the use of this circuit that might not be evident at first glance. The secondary of transformer T_1 (figure 2) is supplying power to the grid of the first tube in amplifier *A*. This power is small to be sure, but due to the internal grid-to-cathode capacitance of the tube, there is sufficient leading current to cause a slight phase shift in the output of transformer T_1. This introduces an error which is not corrected by use of the first feed-back system alone. The secondary of transformer T_2 feeds into the grid of the first tube of amplifier *B*, but its voltage output is balanced against the voltage across R_0, so the only current that can flow in this transformer and cause phase shift will be due to the difference between these two voltages. Normally this difference will be very small and, therefore, the secondary of T_2 will be essentially open-circuited and its secondary voltage will be truly representative of the voltage drop across the shunt regardless of variations in tube grid characteristics, and can be balanced against that portion of the output voltage appearing across R_0 for a true comparison of the input and output of amplifier *A*.

Obviously the effectiveness of this method depends on how much the output voltage must depart from its cor-

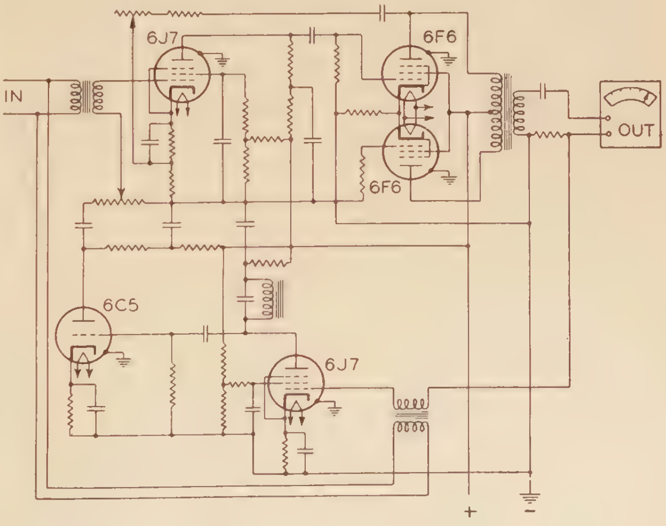

Figure 3. Electrical circuit of stabilized amplifier

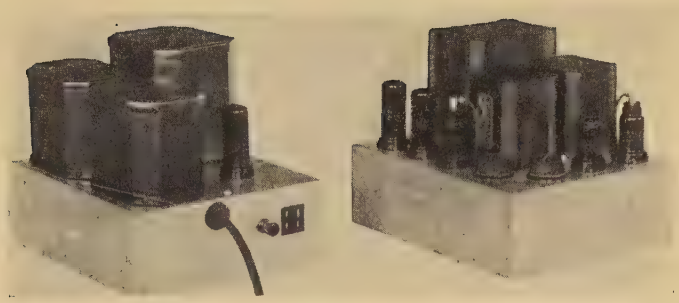

Figure 4. Stabilized amplifier and associated power-supply unit for General Electric 480-cycle a-c network analyzer

rect magnitude and phase to produce the necessary corrective effect. The smaller this voltage the more accurate the balance; the limiting condition being when self-sustained oscillations occur.

The complete amplifier circuit incorporating both systems of feedback is shown in figure 3. The main amplifier consists of a pentode driving a power pentode with a second power pentode connected to the output transformer in such manner as to cancel the d-c flux in the output-transformer core. The internal feedback is made from the plate of the output pentode through a resistance voltage divider to the cathode of the input tube. This connection is necessary to secure proper phasing. The output circuit is tuned with a series capacitor to bring the current in proper phase with the input voltage. The null-balance amplifier consists of a pentode driving a triode with a voltage divider in the triode output to allow control of the correction voltage introduced into the main amplifier. The input pentodes are used because of their low input capacity together with their high amplification and the triode is used in the null-balance amplifier to keep the resistance value of the voltage divider as small as is practicable. Commercially available parts are used throughout. A photograph of the amplifier and associated power supply is shown in figure 4.

The amplifier circuit constants are quite conventional. The plate circuit of one stage of amplifier *B* is tuned at 480 cycles; this increases the feedback through *B* that can be obtained before oscillations occur. This particular method of phase-angle control limits the useful frequency range of the amplifier, but it is not detrimental in this application because the frequency will not vary more than a few per cent from 480 cycles. In many cases it is advantageous to discriminate against harmonics; however, if a band of frequencies must be covered, then other methods of phase angle control will have to be used.

Accuracy and Stability

This particular amplifier utilizes feedbacks of approximately ten to one in amplifier *A* and 70 to 1 due to amplifier *B*. The errors are reduced by a factor of 700, so the extreme case of a 70 per cent change in amplification of one tube only affects the over-all stabilized amplification by one-tenth per cent. The stabilizing effect is so great that the over-all amplification characteristics are substantially unaffected by changes in the amplifier.

It would be possible to increase the feedback in amplifier *A* to many times the above value,[3] but in this particular application the extra stability was not necessary and the simplicity of a two-stage amplifier seemed advantageous. Likewise, the effectiveness of the feedback due to amplifier *B* can be increased providing that the various phase shifts occurring in amplifiers *A* and *B* can be controlled to eliminate self-sustained oscillations, but the extra complications involved did not seem warranted for this application. The amplifier shown tends to oscillate if the feedback due to amplifier *B* is made greater than about 100.

To insure the highest accuracy possible each amplifier is adjusted for phase angle and magnitude with its respective indicating instruments. The stabilizing effect is adequate to take care of the normal ±10 per cent variation in instrument reactance between zero and full scale.

The input-output ratio can be maintained so precisely by using these two stabilizing systems that ordinary instruments are not accurate enough to use in obtaining the initial adjustments. By virtue of the null-balance circuit the input to the null-balance amplifier represents any over-all error in magnitude or phase angle between the input and output, so the initial adjustments are made until the output of this amplifier is zero. The ratio of amplifier *A* is controlled by varying the amount of internal feedback and the phase angle of the output current is adjusted to compensate for the inductance of the indicating instrument by means of a series capacitor.

An indicating device can be connected to the output of the null-balance amplifier and used as an indicator to show if the amplifier is working properly. In the network analyzer application this was not thought to be necessary because a circuit is provided, to which the amplifiers may be connected, and in which the voltage and current are adjusted to give predetermined deflections on the voltmeter, ammeter, and wattmeter. By connecting both amplifiers to this "standard circuit" they can be checked one against the other. This is not used as an absolute calibration for the instrument system but it does serve to increase the reliability for, if the readings do not check, something must be wrong with one or both measuring circuits.

Several of these amplifiers have been made and calibration tests indicate an accuracy of better than one-tenth per cent in magnitude and ten minutes in phase angle. The amplifiers are rated one-half per cent and 20 minutes. Tubes can be interchanged freely, and line-voltage variations on the amplifier power supply of 20 per cent do not change the calibration; however, when using high-speed light-beam instruments, severe transients in the 60-cycle power supply will cause the light beams to jump, after which the reading returns to the correct value. To eliminate this, a regulator can be placed in the 60-cycle supply to the amplifier power units to remove these transients. After being in constant use for eight weeks, two amplifiers and their associated indicating instruments were found to have a maximum deviation from their original calibration of two-tenths per cent of full scale without any readjustment.

Conclusion

With the proper use of stabilizing circuits, electron-tube amplifiers can now be built that are just as accurate and reliable as, and in many respects better than, the indicating instruments with which they are to be used. Such amplifiers combine the characteristic low power-input requirements of vacuum tubes with the accuracy and reliability found in high quality measuring instruments.

The use of stabilized amplifiers may be extended to any application where accurate measurements are required of quantities too small to be measured any other way. Their proved accuracy and reliability should go a long way toward getting around the average engineer's inhibitions against the use of electron tube apparatus whenever accurate and reliable measurements must be made.

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3. STABILIZED FEEDBACK AMPLIFIERS, **H. S. Black.** ELECTRICAL ENGINEERING, January 1934, volume 53.

Discussion

H. L. Hazen (Massachusetts Institute of Technology, Cambridge): This paper, in my opinion, describes a significant development in the field of electrical measuring instruments. By the technique here described it is practicable to attain a new order of speed of response and accuracy in rugged, low-burden instruments. It appears that the possibilities of this technique are numerous where the accuracy and speed of standard portable instruments are desired with burdens that are a minute fraction of those imposed by such portable instruments themselves.

Apart from the significance and utility of the design as a whole, there are several questions regarding the details on which I should like to comment in this discussion. There are two types of feedback employed in this amplifier which for the most part are mutually helpful. One of these feedbacks—the linear feedback—is actuated by the output voltage. The other—that due to amplifier *B*—is actuated by output current. It appears that in a device of this sort, in which the indicating instrument inherently responds to current rather than to voltage, the amplifier should be so designed as to maintain the desired mutual conductance of the unit as a whole. That is, for any given input voltage a definite current proportional to this voltage is desired in the indicating instrument. It appears that feedback based entirely on output current rather than on voltage or a combination of voltage and current, is therefore desirable.

A theoretical analysis of this amplifier has been made with Mr. G. S. Brown to determine the effects of these feedbacks and to compare them with other feed-back schemes. One basis of comparison is the ratio of the fractional change in mutual conductance to the fractional change in another variable, such as the gain of amplifier *A*, the impedance of the output circuit, or the internal impedance of amplifier *A* as viewed from its output terminals. With the scheme as used, it appears that the fractional change in the mutual conductance is about one seven-hundredths of the fractional change occurring either in the gain of amplifier *A* or in its internal impedance as viewed from its output terminals. In contrast, the fractional change in the mutual conductance is not one seven-hundredths, but one-seventieth of the fractional change in the load impedance because the linear component of feedback is based on output voltage rather than output current. If a comparable amplifier is made in which the feedback is all based on output current, the change in the mutual conductance caused by changes in amplifier-*A* voltage ratio, by changes in amplifier-*A* impedance as viewed from its output terminals, or by changes in the load impedance—all become the same. It appears, therefore, that for a device of this sort, feedback based on output current rather than on output voltage is desirable.

It is stated in the paper that one advantage of using the type of feedback involving amplifier *B* is that it tends to make the voltage actually applied to the input terminals of amplifier *A* approach zero, and therefore reduces the current drawn at the input terminals of this amplifier. This statement seems open to discussion on two counts: First, it can be seen that if amplifier *A* and its linear component of feedback are suitably adjusted, the input to amplifier *B* is zero, and its output voltage is therefore necessarily zero. Hence it appears that amplifier *B* does not have any effect on the magnitude of the amplifier-*A* input voltage unless amplifier *A* and its linear component of feedback are out of adjustment.

Second, any degenerative feed-back scheme—linear or otherwise—serves the purpose attributed to amplifier *B*, namely, it puts a voltage in series with the signal input voltage which has such polarity and magnitude as to make the sum of these voltages small compared with either. Thus, assuming the amplifier-*B* scheme of feedback to be functioning, it does nothing that any other feed-back scheme would not do on this count.

Another way of considering the relative magnitudes of signal voltage and actual amplifier input voltage is this: For a given amplifier output and amplifier gain, the input voltage to the amplifier is fixed. If the amplifier mutual conductance is N times the desired ratio between output current and actual signal voltage, then the net amplifier input voltage is necessarily only $1/N$ of the signal voltage. This, as was pointed out above, is characteristic of any degenerative feed-back amplifier and not merely of the particular type of feedback represented by amplifier *B* in this circuit.

In raising the foregoing questions I do not wish to detract in any way from the value of this development. On the contrary, the contribution seems so significant in the measurement field that it is worth while to give attention to matters which may be relevant to the design of similar units in the future. The foregoing comments are based primarily on theoretical considerations, and I shall be glad to have the author's comments, both from the theoretical and from the practical point of view.

F. K. McCune (General Electric Company, Lynn, Mass.): Mr. Thompson's paper should be of universal interest to those concerned with electrical measurements. The combination of circuits described appeals to me as particularly ingenious since it compensates not only for magnitude of current but for phase angle as well. I feel that this latter feature is deserving of special comment since the accuracy of correction is such as to be perfectly adequate for the great majority of measurements. The value of ten minutes of phase angle corresponds to one-half per cent at 50 per cent power factor, however, and is therefore too large to neglect for very accurate measurements of power or vars. It will be of interest to see whether the continued use of these circuits shows greater accuracy possible.

A possible field of application for this circuit would seem to be the measurement of extremely small currents such as are dealt with in noise and vibration measurements. Here the effect of "pick up" from extraneous sources, both of noise and vibration, may affect the readings obtained, due to the disturbances they produce in the amplifiers. If the frequency range of the circuits described can be made large enough, it would offer a possible solution to many troublesome problems of this sort.

It would seem from a rough examination that while phase-angle errors in *A* would be corrected by *B*, that phase-angle errors in *B* would result in considerable errors. For example assume currents in the shunt and in R_0 initially ten minutes out of phase. If amplifier B should have a ten-minute phase angle and the result should be subtractive, an out-of-phase current with a magnitude of a fraction of one per cent would be impressed on B and would be there amplified and impressed on A exactly in phase. The result would be no improvement in phase angle and an increased error in magnitude.

Probably this is only a theoretical possibility, but calibration data on the circuits will, no doubt, be taken periodically and will give the real answer to all such considerations.

M. S. Mead (General Electric Company, Schenectady, N. Y.): In the discussions of Mr. Thompson's paper, "Stabilized Amplifiers for Network Analyzer," there appear to be four points which should be answered. Mr. McCune mentioned that in a wattmeter, even a very small phase-angle error will result at low power factor in considerable error. This is a well-recognized difficulty in all wattmeters and in this case the answer simply is that extreme accuracy in power or var measurements at low power factor is not required. So far, in the operation of the board, the accuracy of the watt and var measurements has been great enough, even at low power factors, so as not to handicap the operation of the board in any way.

The second point he raised was in connection with the effect of phase-angle error in amplifier B on the phase-angle error of amplifier A. Without taking the time to submit a proof, it may be stated that with large amounts of feedback, any small departure from 180-degree feedback will result in an infinitesimal reduction in the benefits secured from the feedback. Therefore, we conclude that a small phase-angle error in amplifier B is unimportant.

I know that Mr. Thompson appreciates the nice things Prof. Hazen said about the development. In his discussion, Prof. Hazen mentioned two things. He stated that it would have been better to have designed the amplifier so that 700 times current feedback was used alone without the voltage feedback. Others have offered the same comment. We are in entire agreement with this thought. However, it is extremely difficult to build an amplifier including an output transformer and having a feedback ratio of 700. Confronted by limitations of time and facilities, nevertheless, a feed-back ratio of 700 was secured by using the compound effect of two separate feedbacks, each of which was quite easy to get.

The second point Professor Hazen mentions apparently resulted from some misinterpretation of the text. The paper stated that there was a distinct benefit secured from using external feedback and a reference voltage derived by an additional transformer across the current shunt. This advantage is not concerned with the amount of grid voltage input to amplifier A as Professor Hazen understood was claimed, but rather to amplifier B whose input voltage approaches zero and consequently the amplifier cannot act in any manner as a load on the transformer supplying the reference voltage.

H. A. Thompson: The discussion seems to center around the question of just which feedback is the simplest and best. Considering that the particular instruments used respond to current rather than voltage, as Professor Hazen has mentioned, it is advantageous to use current feedback and control the transconductance of the amplifier rather than the voltage amplification.

The time at our disposal to develop this amplifier was limited and a conservatively rated two-stage amplifier with feedback appeared to be the simplest and most reliable unit we could assemble and still get the required amplification. The null-balance amplifier B was added to serve as a check on the performance of amplifier A and also to compensate for the variation in instrument inductance and the mutual voltages introduced in the wattmeter coils. No trouble was experienced due to the effects of phase shifts in B. If necessary, it would have been a simple matter to stabilize B with negative voltage feedback similar to that used in A. As a matter of fact, tests indicated that the tuned circuit used in amplifier B could be detuned considerably without any harmful effects.

Doubtless, if the time and money were available, this amplifier could be improved, but for this particular application the accuracy and reliability needed did not warrant any further development. Operating experience has indicated that the amplifiers perform well within the operating requirements of the network analyzer. In fact, the wattmeter has been used at power factors as low as seven per cent with acceptable accuracy, and phase angle measurements are made using the wattmeter at zero power factor.

Phanotron Rectifiers as a D-C Supply for Elevator Motors

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Introduction

THERE ARE a number of public utilities that have instituted programs for curtailing and in some cases completely eliminating the d-c power supply to concentrated load areas. The change from d-c to a-c power supply for elevators in the affected areas requires the substitution of a-c elevator equipment or the use of converters to supply d-c to the existing elevator equipment. Elevators may be operated equally well from either alternating current or direct current, so the choice is dependent upon the cost of the change-over.

Where a converter is to be used, a phanotron rectifier possesses many advantages. Its first cost is competitive with other forms of converters. It has no rotating parts and so requires no special foundations, and it is quiet in operation. These two characteristics permit greater freedom in selecting the location of the converter. It is more efficient than a motor generator set. It is semiautomatic in operation, thus requiring little attention from the building attendant.

The phanotron rectifier used for elevator power supply is of particular interest as it is the first industrial application of the modern type of metal electron tube in power sizes. In addition the automatic features incorporated in these rectifiers have resulted in a very successful service record and consequently merit the careful attention of those interested in applying electronic equipment for power purposes.

Before describing the phanotron rectifier and considering its features, the power requirements of elevators will be reviewed.

Power Requirements of Elevator

Elevators with few exceptions are simple counterweighted hoists in which counter weight generally equals that of the cab and its appurtenances, plus 40 per cent of the cab capacity. The motor load is characterized by peak power consumption during the starting and accelerating period followed by a very much reduced load during the running period, which depends upon the number of passengers in the cab, and may be regenerative in character, followed by regenerative braking to a slow speed or stop. The current required to accelerate full load may vary from 100 to 250 per cent of the current required to hoist full load. The usual maximum regenerative load on gearless installations is approximately 48 per cent of that required to hoist full load, and on geared installations, 23 per cent.

Where there is more than one elevator in an installation, it is impossible to predict the load demand from the speed and capacity of the various elevators. The average elevator does not operate more than 50 per cent of the time that it is in service. Since the loading is usually directional with respect to time of day, maximum load will not be required more than 25 per cent of the operating time. Consequently, the ratio of maximum to average load will be high where only a few elevators are involved in a given plant. As the number of elevators increases, the ratio reduces and the short time power peaks become less pronounced. The type of motor used also has a considerable effect on the shape of the power demand curve. A typical elevator load is shown in figure 1.

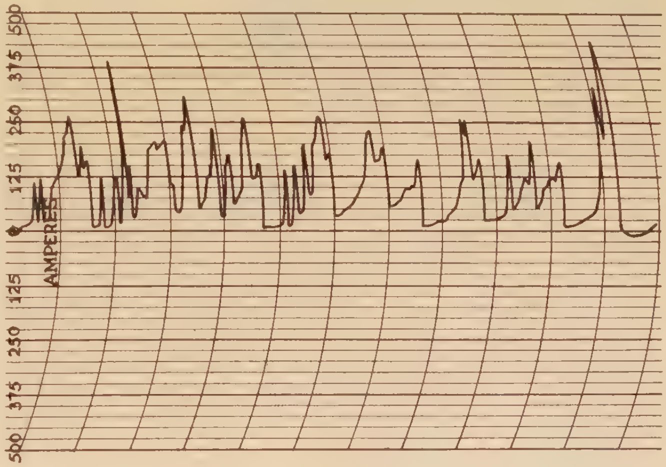

Figure 1. Typical load on a bank of three elevators with 35-horsepower motors

If load curves can be obtained during times when the elevators carry heaviest loads, the maximum momentary peak current, the average current, and the root mean square current may be estimated and used as a basis for determining the size of the phanotron converter.

The First Installation

In the fall of 1935, a trial installation was made in Chicago using a four-tube rectifier operating from a power supply of 208 volts, 3 phase, 60 cycles, and delivering direct current at 230 volts. Operating data obtained before the change-over showed instantaneous peaks in excess of 200 amperes. These peaks and the fact that the only phanotron tube in this current range was rated 30 amperes average with a momentary peak commutating capacity

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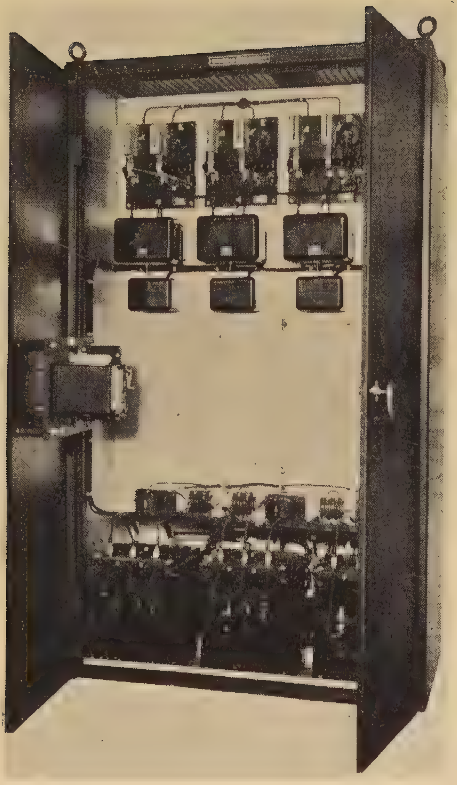

Figure 2A. Front view of rectifier with doors open

of 150 amperes, necessitated the use of a double single-phase circuit with an interphase transformer to obtain the required momentary peak capacity. The original design included anode fuses to protect the rectifier. Soon after this unit was placed in service, a tube arc-back or short circuit blew the anode fuses and left the elevator stranded between floors. This occurrence clearly indicated the necessity of eliminating the fuses, and in addition, providing reserve rectifying capacity in order to maintain service in event of a tube failure.

Phanotron Rectifier

A modified rectifier design using six phanotron tubes, anode contactors, thermal overload relays, and reclosing timers was then built. It operated so successfully that all subsequent rectifiers for elevator service have followed this same fundamental design.

The general appearance of the rectifiers is shown in figure 2. It consists primarily of phanotron tubes mounted in the middle section, with power transformers and interphase transformers mounted in the base. The associated control and protective equipment is mounted upon a panel within the cubicle, and the cubicle is provided with two full length hinged doors to give ready access to all parts of the rectifier. The tubes are enclosed in an individual section at the back of the cubicle, which extends the length of the rectifier, access being provided by two small hinged doors inside the enclosure. This compartment is in effect a chimney providing the proper ventilation to maintain the tubes at the desired operating temperature. The screened opening through which the ventilating air enters is located at the rear of the cubicle.

To date, there have been built seven 230-volt units and three 550-volt units. These range from 25 kw for one hour to 40 kw continuously at 230 volts, and 50 kw for one hour at 550 volts.

These rectifiers are usually described by a one-hour kilowatt and a peak-current rating as the elevator load is directional and highly concentrated with respect to time of day.

Phanotron Tubes

The phanotron tube used in the elevator type of rectifier is of the directly heated hot-cathode type, with a metal envelope, internal insulated anode, and mercury vapor. The tube (This tube bears the trade designation *FG*-166.), figure 3, is designed to operate at condensed mercury temperatures of from 20–80 degrees centigrade. This range corresponds to an ambient temperature of from 20 degrees to 50 degrees centigrade. Before a rectifier of this type can be placed in service, the proper vapor conditions must be established inside the tubes and the filaments must be brought to the emitting temperature. To accomplish this, the filaments should be energized for a short period of time, one to two minutes under ordinary conditions or a longer time if low ambients are encountered. If the rectifier is to be placed in a position where the ambient goes below five centigrade, thermostatically controlled dampers or louvers are used in the ventilating system to assist in maintaining the proper operating temperature of the tubes.

The average expected life of this type of tube is 10,000 hours when operated under conditions described here. Four installed in October 1935 have already given approxi-

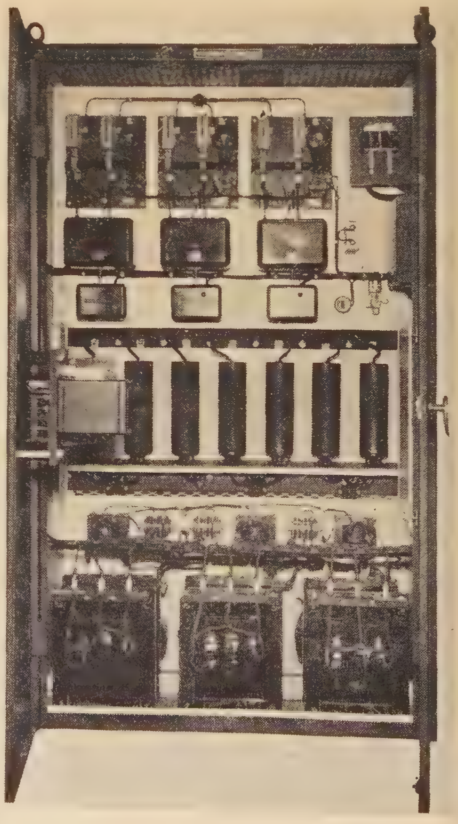

Figure 2B. Front view of rectifier with main door and tube-compartment door open

mately 16,000 hours service and twelve installed in January 1936 have been operating continuously with no failures.

Triple Single-Phase Full-Wave Circuit

In a single-phase full-wave connection, each tube carries current for 180 electrical degrees. The tube used in the rectifiers has an average rating of 30 amperes with a peak rating of 150 amperes. Thus, such a single full-wave rectifier would have an average current rating of 60 amperes and a maximum momentary peak rating of 150 amperes. Likewise, three such rectifiers, one connected to each phase of a three-phase supply, and having their cathodes paralleled through interphase transformers, would have a combined rating of 180 amperes, and a momentary peak rating of 450 amperes. This arrangement of connections will be called a triple single-phase circuit. The triple single-phase full-wave circuit has the additional advantage of balancing the load on the three-phase supply. Also this arrangement increases the ripple frequency and reduces its magnitude because of the 120-degree displacement resulting in a smoother d-c voltage. Considering motor generator sets, however, I would say that the set had a continuous rating of 180 amperes and a maximum commutating peak capacity of 450 amperes which the generator could safely produce. The single-phase circuit makes possible the maximum utilization of the current carrying capacity of the tube resulting in greater reliability of operation and longer tube life than is obtainable in any other type of circuit so far available for intermittent service.

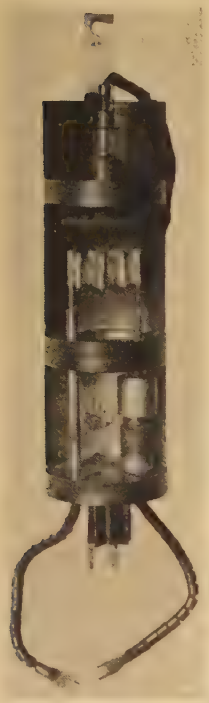

Figure 3 (left). FG-166 hot-cathode tube used in rectifiers

The experience gained on the four-tube rectifier indicated the desirability of using a circuit which would have enough reserve capacity to keep the elevators in service in the event of a tube failure. The triple single-phase full-wave circuit accomplishes this purpose as it may be operated as a double single-phase full-wave circuit and produce two-thirds of its rated output simply by opening the circuit having a faulty tube as an inspection of the elementary circuits will show this possibility.

The power and control circuits are shown on figure 4, elementary a-c control diagram; figure 5, elementary diagram of power circuit; figure 6, elementary d-c control diagram.

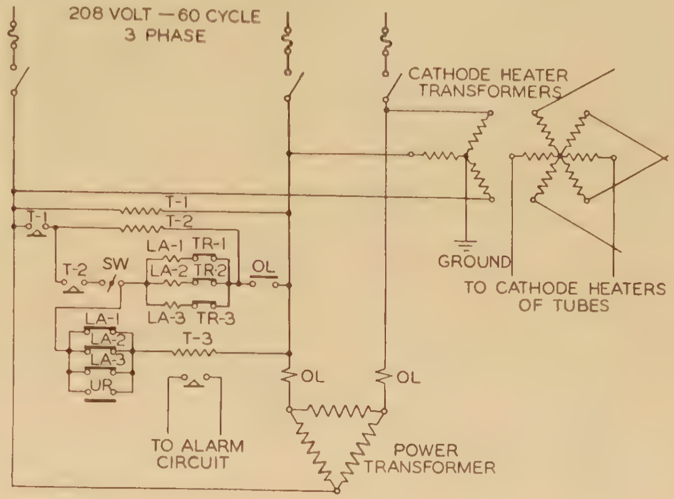

Figure 4 (right). Elementary a-c control diagram

T-1—Cathode-heater timing relay
T-2—Reclosing timing relay
T-3—Alarm relay circuit
*LA*1, 2, 3—Thermal relays
*TR*1, 2, 3—Thermal relays
OL—Overload relay
SW—Control switch
UR—Unbalance relay

Functions of Semiautomatic Control

In case a tube arcs back, the a-c overload relay (*OL*) opens the coil circuit to the anode contactors which immediately open. After two seconds the anode contactors are reclosed by reclosing relay (*T*2). If the trouble persists after several reclosures, one of the three double-pole temperature overload relays (*TR*-1-2-3) in the faulty circuit will open the coil circuit of its associated anode contactor and operation will be continued with the remaining phases and four tubes. The tubes are removed in pairs because the failure of one tube in a single-phase full-wave circuit produces saturation in its anode transformer and also reduces the average output voltage resulting in the remaining tube carrying practically no current. The opening of the contactor in one single-phase circuit changes the ripple frequency causing the operation of unbalanced relay (*UR*). The operating coil of this relay forms a part of a series tuned circuit connected across the d-c output (see figure 6). The unbalanced relay (*UR*) operates a relay (*T*3) to close the user's alarm or indicating circuit. If the disturbance has been one of repeated arc-backs, the defective tube can be identified through its element of the temperature relay in that phase.

If the tube fails to conduct because of lack of emission, the unbalanced relay (*UR*) will operate the alarm, no other relays operating. In this case the anode contactors will not be open, but the defective tube can be identified by its lack of the characteristic blue glow as seen through the anode seal at the top of the tube. In order that a spare tube may be placed in operation, provision is made for holding it between the active tubes so that the radiated heat will keep it warm and the mercury properly distributed.

On the occurrence of a severe overload the control functions in the same manner as that for an arcback. If the overload persists for less time than required for the thermal relays to operate the anode contactors will reclose and normal operation will be resumed.

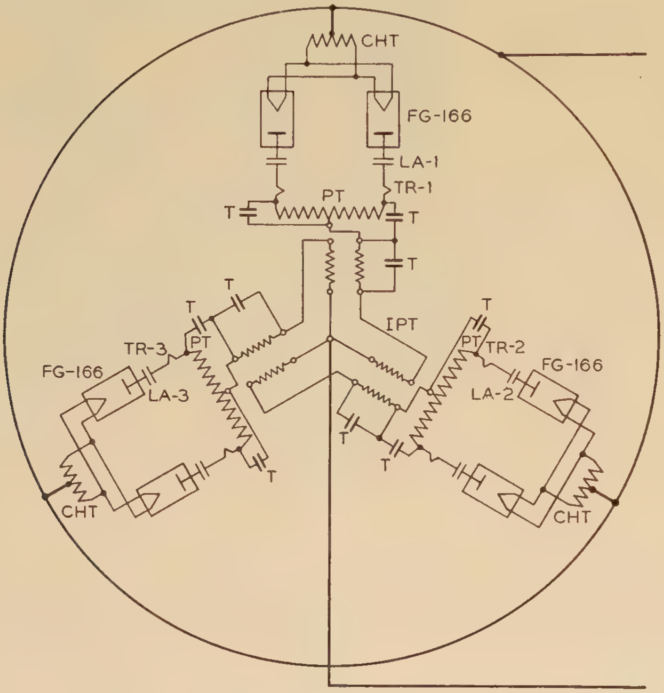

Figure 5. Elementary diagram of power circuit

CHT—Cathode-heater transformer
FG-166—Phanotron tube
IPT—Interphase transformers
PT—Power transformers
*LA*1, 2, 3—Anode contactors
T—Thyrite arresters
*TR*1, 2, 3—Thermal relays

When connecting the rectifier to the source of supply, the cathode-heating transformers (*CHT*) (figures 4 and 5), are energized and supply excitation to the tubes. A timing relay (*T*1) is energized and after a predetermined time applies voltage to a reclosing timer (*T*2). In two seconds, voltage is applied to the closing coils (*LA*-1, 2, 3) of the three-tube anode contactors provided the control switch (*SW*) is closed. The closing of these contactors completes the circuit and makes power available.

The rectifier may be removed from the d-c load by opening switch (*SW*) which de-energizes contactors (*LA*-1, 2, 3) and opens the power circuit of the rectifier. However, the cathode-heater transformers remain connected to the power supply so that upon closure of *SW*, the rectifier is immediately reconnected to the load. Opening of the a-c power supply de-energizes the timing relay and power transformers. For the resumption of operation upon reclosure of the power supply switch, the timing cycle must be repeated after which the rectifier can be returned to service.

Overhauling Load

When the elevator is lowering a sufficiently heavy load, it holds speed by regenerative braking. Since the elevator rectifier cannot return this power to the supply circuit, it is necessary to provide a loading resistor which will absorb it. The loading resistor (*R*3) is shown in elementary d-c control diagram, figure 6.

The operation of the regenerative loading circuit is as follows: if power is supplied to the d-c output circuit, the coil of timing relay (*T*4) is energized through the loading resistor (*R*3), which relay completes the circuit of the instantaneous voltage relay (*VR*). When the rectifier operates with an overhauling load, the voltage on the d-c bus rises sufficiently above no load voltage to actuate voltage relay (*VR*) which in turn closes the loading resistor contactor (*L*) and allows it to absorb the overhauling load. The closing of contactor (*L*) also de-energizes the operating coil of the timing relay (*T*4), which after four seconds drops out, opening the voltage relay coil circuit so that the control is ready to repeat the cycle if the regenerative condition persists. As the regenerative power usually exists for much less than four seconds, generally one operating cycle is sufficient.

Power and Interphase Transformers

The transformers employed in these rectifiers are of the natural-draft air-cooled type as this construction provides the most economical design. As the transformers are located inside the cubicle (see figure 2) individual enclosing cases are not required. Transformers operating in rectifier circuits are subjected to transients during faulty operation. To protect the windings against any surge voltages that may be induced at such times, thyrite resistors (*T*) in figure 5 are connected across power transformer secondaries to neutral, and across one winding of each interphase transformer.

R-1—Loading resistor
UR—Unbalance relay
CAP—Capacitor
VR—Voltage relay
R-2—Variable resistor
T-4—Timing relay
L—Contactor
R-3 — Regenerative loading resistor

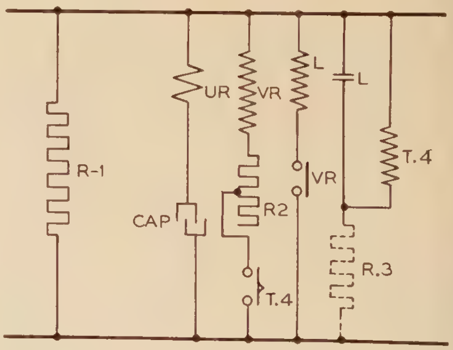

Figure 6. Elementary d-c control diagram

The triple single-phase circuit requires three interphase transformers. Each transformer has two independent sections connected zig-zag in order to cancel the d-c ampere turn under balanced load. The connection is equally effective with either two or three single-phase circuits in operation.

The design of the interphase transformer is of special importance in this particular service as the magnetizing current determines the point of inflection of the voltage regulation curve, figure 7. Slight manufacturing variations will naturally be encountered in similar circuits of identical design; hence, the d-c current supplied by each rectifier circuit will be different. To prevent saturation due to any small unbalance that may be present, the interphase transformers are constructed with an air gap. The magnetizing current being roughly proportional to the air gap, a small air gap is desirable in order that the inflection points occur at as light a d-c load as possible.

To provide the desired interphase transformer characteristics, the air gap is slotted, that is there is a small section of iron in the gap which produces a low-impedance flux path at light load, but which saturates very early under increased load, and so effectively lengthens the air gap. To prevent a high no-load voltage, a small loading resistor (*R*-1) (figure 6) rated 1.6 amperes is permanently connected across the d-c output. Its loss is only a small percentage of the no load loss of the rectifier.

Voltage Regulation

With the loading resistor in the circuit, the voltage at no load is about 257 volts and the voltage regulation of the elevator rectifier is approximately ten per cent as shown by the flat portion of solid line in figure 7. The dotted curve in figure 7 shows the regulation which would be obtained if one branch of the triple single-phase circuit were not operating. This latter regulation has been found to be sufficiently good to maintain substantially normal operation of the elevators.

Efficiency and Power Factor

The efficiency curve of the 40-kw, one-hour, 230-volt rectifier is very flat as shown in figure 8. This is materially better than can be obtained from a motor generator set of like rating, particularly at the light loads which are usually encountered with most elevator plants because of their low load factor. No-load losses are approximately 2.4 kw.

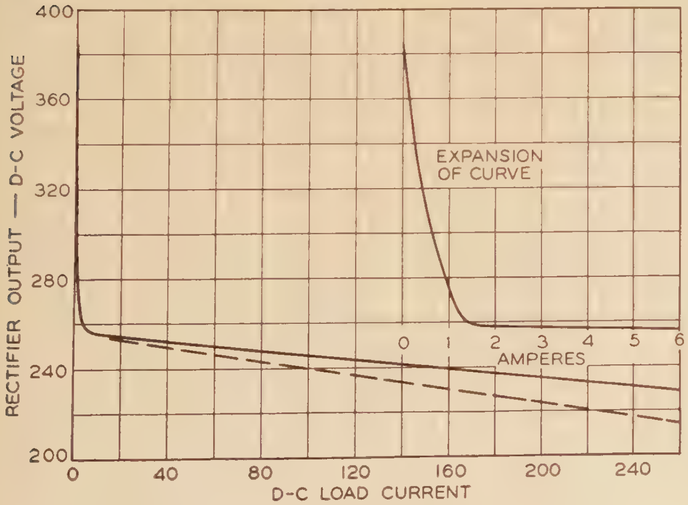

Figure 7. Voltage-regulation curve

Figure 8 also shows the input power factor. It will be noted that this is very good even at no load, where the power factor is approximately 0.77. This is contrasted with a motor generator set having a no load loss of approximately 3.5 kw at a power factor of 0.25.

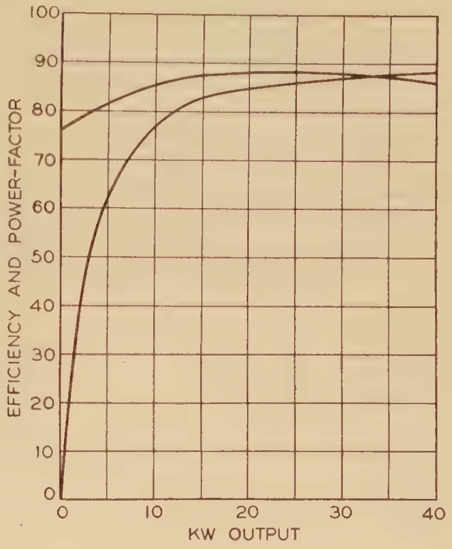

Figure 8. Power factor and efficiency 25 kw continuous; 40 kw, one hour, 240 volt, rectifier; no-load loss 2.4 kw

Summary

The triple single-phase phanotron rectifiers at the present time are built in capacities up to 40 kw at 230 volts and 75 kw at 550 volts. Their application has not been confined to elevator loads, one having been applied to general machine shop load including cranes, and another handling the entire building load elevators, ventilating fans, pumps, etc.

The units are self-contained with all live parts enclosed and if desired the cubicle may be locked. The installation wiring is limited to bringing in the a-c supply and connecting the d-c load. Installation costs are thus held to a minimum.

The operation of the seven rectifiers in service has to date been entirely successful. Additional rectifiers have been purchased by the original users after one year of use, indicating the suitability of the rectifier for hoisting service.

Discussion

T. G. Glenn (General Electric Company, Chicago, Ill.): There are at present five 40-kw and two 25-kw, 250-volt phanotron rectifiers furnishing power for elevator equipment in the Chicago Loop area.

These rectifiers supply power for elevators, both freight and passenger, which in the majority of cases are in service 24 hours a day, seven days a week, so that the phanotron equipment is energized continuously. Because of this continuous service it is essential that the equipment operate with high no load efficiency.

The installations in the Chicago Loop area have been very successful and given remarkably satisfactory service. As the buildings in which they are installed are of a smaller office and manufacturing loft type, the electrical maintenance force is not of the caliber to give equipment the type of maintenance that rotating apparatus would require. In fact the equipments since their installation have seen little or no maintenance, and several of them are covered with dust and have not been inspected in months.

This is a condition, of course, that is not desirable and one which has been called to the building managements' attention, but it does indicate that the phanotron rectifiers will operate with little or no attention.

It has been found desirable to make complete load checks before recommending the size of conversion apparatus, or the size of resistor for regenerative braking. Load tests have been of an advantage as elevator equipment in most instances is old and nameplate ratings do not indicate the true capacity of the equipment.

As these phanotron rectifiers were installed in buildings where most of the available space is in use, rectifiers must be installed where space is available, sometimes this in the the basement and sometimes in an out of the way corner on one of the floors of the building. Our experience has shown that locations that were not suitable for rotating apparatus could be used for the rectifiers.

At first the electrical contractors who in general are installing the phanotron rectifiers, were skeptical of the equipment. This attitude perhaps was due to the equipment being new and unfamiliar to them, and contained electronic devices. However, the extreme simplicity of installation and wiring appeals to them. For instance, the wiring of a phanotron rectifier equipment requires only the installation of a three-wire incoming a-c line and a disconnect switch, and an outgoing two-wire d-c line to connect the load sides of the rectifier with the existing d-c mains in the building.

The long tube life experienced in these installations indicates a low maintenance cost.

The operating experience of the phanotron rectifiers in the Chicago area has shown that these units if properly installed, will furnish service comparable to that supplied from a 250-volt d-c system of the power company.

Transmission Line Transients in Motion Pictures

By L. F. WOODRUFF
MEMBER AIEE

IN SELECTING subjects for educational treatment by motion pictures at Massachusetts Institute of Technology, one of those favored was that of traveling waves on transmission lines. Reasons for the selection included the mathematical complexity of the subject and the difficulty of teaching it without spending an undue amount of time, and the fact that the phenomena which are involved are functions of both time and distance, and hence difficult to illustrate or visualize by ordinary methods. Experience in the use of the films with classes has shown that students' general understanding and appreciation of the subject are indeed greatly improved by viewing the motion pictures. The films which have been prepared have been and are now available in both the 16- and the 35-millimeter widths for free loan to other technical schools and associations.

In undertaking the work, it was decided that a true picture should be presented as far as was reasonably practicable. Waves computed on the basis of neglecting resistance and leakage would be very easy to show, since the resulting waves would be purely rectangular in shape. This method could not even allow showing the settling to the steady state. Computing the waves from the formulas for the distortionless line case ($R/L = G/C$) would be relatively easy, but the results would not be very appropriate since this condition presupposes an amount of leakage which is much greater than that present on any ordinary line. Furthermore, both of these foregoing methods involve neglecting skin effect and any other phenomena which result in the departure of the wave front from the vertical.

A better method of computing, but one which still neglects the factors which lead to a rounded wave front, is the one which results from the analysis based on uniformly distributed line constants of resistance, inductance, and capacitance. This is not an easy method to apply numerically, but it was felt that at least one case should be treated in this way, if only for comparison with other results.

Computation of wave distributions with skin effect taken into account can be worked out by brute-force methods, such as representing a suddenly impressed voltage by a Fourier's series of period sufficiently long to allow the line to settle practically to a steady state before the following impulse comes on. This settling to the steady state may be hastened by having the line loaded by a resistance equal to its surge impedance. A tremendous number of harmonics however must be handled even to approach fairly closely to the actual solution for a single time and position on the line. When it is considered that literally thousands of complete curves of distribution are required for the motion pictures, and further that it is desirable to treat cases in which the reflection at the load would add further great complexities in the calculation, it is seen that this method is not possible to apply in any reasonable time or at reasonable expense. Steinmetz[1] has made a very rough use of this method, but without the device of adding the surge-impedance load to hasten subsidence.

A rather meager amount of progress has been made in more direct mathematical attacks upon the problem of traveling wave behavior with skin effect taken into account, but there is no formula as yet developed which yields a solution sufficiently precise for the purpose at hand, or sufficient economy of time and effort to warrant its use for such a purpose.

Attention was turned therefore to methods of determining the data experimentally. The ideal source for the data would be a long actual power transmission line, but the practical difficulty of getting the use of such a line over a long enough period, and of taking observations at a large number of points along the line separated from one another by many miles, were very large.

Fortunately there have been available for a number of years in the electrical engineering laboratories at Technology, artificial transmission lines with distributed constants, designed by F. S. Dellenbaugh, Jr.[2] Comparisons of oscillograms taken of transients on these artificial lines and on actual overhead lines have shown that the characteristics of the laboratory lines are very nearly the same as those of actual lines. It was decided therefore to use, as the chief source of data, oscillograms taken at various points along one of these laboratory lines. Various types of load could be connected, and the transients and reflections resulting from complicated cases could be handled as easily as those from simple cases. A length of 250 miles was selected as being about equal to that of the longest existing lines. Relatively simple cases were selected for first treatment, since the purpose was an educational one.

On account of the rapidity of the transients and the steepness of the wave fronts, it was essential to use a cathode-ray oscillograph. In order to secure a standing image of the transient on the screen of the cathode-ray tube, and to obtain a time datum and comparative voltage datum with respect to the sending-end voltage, a special commutating device was developed to make it possible to give in effect a plurality of traces, of different currents or voltages, simultaneously on the screen. This device has been described in an earlier article.[3]

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1. For all numbered references, see list at end of paper.

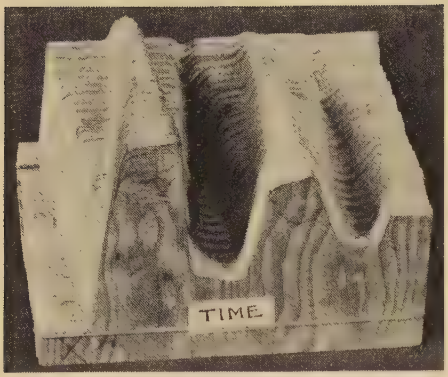


Figure 1. Voltage - time - distance surface representing d-c switching transient on open line

It was decided that the films should be confined to showing variations of voltage, rather than bringing in current variations also, for several reasons. On power lines, when damage is done by traveling waves, it is by high-voltage rather than by high-current effects, and hence the voltage is practically more important. It is also easier to understand the entire phenomenon by watching a voltage wave rather than a current wave, because with the proportionality which exists between voltage and charge on a smooth line, an idea of the current is obtained readily by mentally applying the analogy of a mass of liquid moving along as a wave or surge. The only disadvantage in using voltage rather than current is that in the computation (which was used in one case for comparative purposes) the voltage is much more difficult and tedious to calculate. This disadvantage however can be overcome, as will be seen later.

Each oscillogram is a record of the time variation of voltage at some definite point on the artificial line, whereas the type of curve needed in preparing the motion pictures is a distribution of voltage along the entire length of the line, at a definite single instant of time. It was necessary therefore to replot the oscillographic data, transferring one ordinate from each oscillogram taken under a given set of line conditions, to a distribution curve. This was done by carefully ruling off all the 32 oscillograms which were taken for each case, by equal time intervals, and making use of a pair of proportional dividers to transfer and scale down the voltages recorded, at a particular length of time after energizing the line, on all the 32 oscillograms, to the distribution curve for that particular instant. Corrections for nonlinearity of the sweep time axis and other distortions were made in this process.

Direct Voltage on Open Line

The first case treated was that of the open-end line, with direct voltage suddenly impressed on the uncharged line at the sending end.

As an aid in visualizing the three-dimensional variation involving distance, time, and voltage, tracings of the oscillograms were made and glued to sheets of plywood, and then cut out along the curves by means of a jig saw. When these pieces are assembled in order, they form a three-dimensional plot of the variation of voltage, during the transient period, with both time and distance. A photograph of this solid figure for the open-line case is reproduced in figure 1.

With reference to this solid figure, each voltage distribution curve may be visualized as a thin slice of the figure made in a direction perpendicular to the plane of the plywood pieces and to the base.

The voltage distribution curves for a number of instants of time are shown in figure 2. It is seen that the wave undergoes attenuation and distortion during its travel, and the wave front becomes progressively less and less steep. Complete reflection at the open end takes place without a change of sign, resulting in a voltage nearly twice the impressed voltage for a short time. Reflection

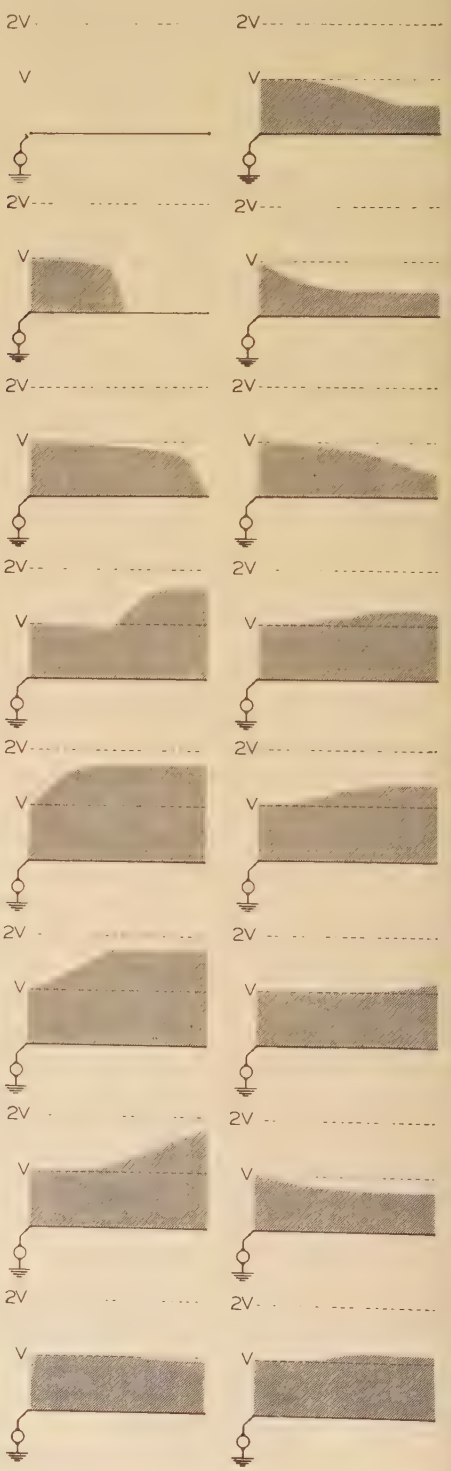


Figure 2. Direct-voltage waves on open line

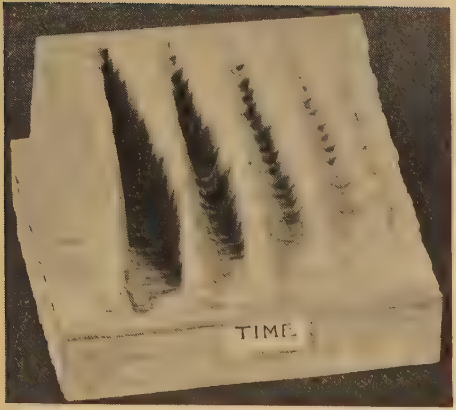


Figure 3. Direct-voltage switching transient on short-circuited line

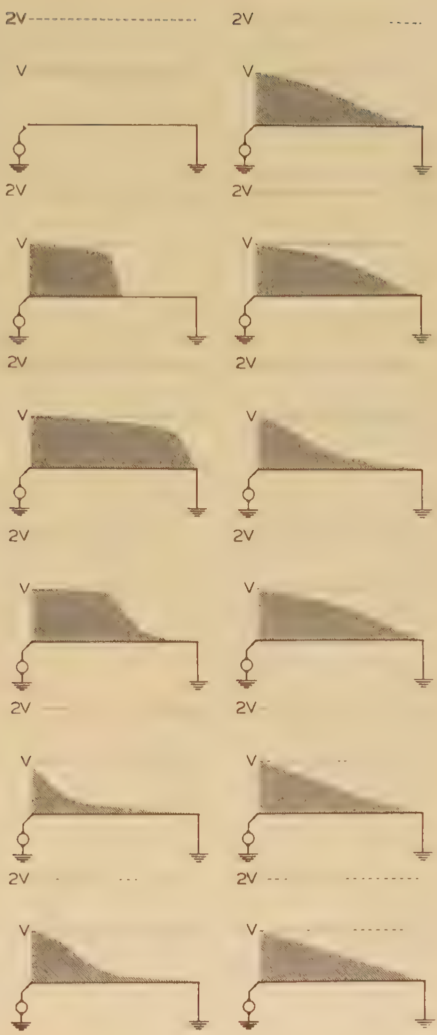


Figure 4. Direct-voltage waves on short-circuited line

at the sending end occurs with a reversal of sign, and after several trips of the wave over the line the distribution is obviously approaching the steady state of a voltage along the whole line equal to the impressed voltage. This is in the absence of any appreciable leakage on the line.

Technique of Actual Photography

When distribution curves had been plotted in the manner already explained, dark paper cutouts were made with scissors to fit the distributions. These were then glued to white paper background sheets, which had perforations to locate them precisely over pins on a platform under a motion-picture camera. The procedure was quite similar to that used in animated cartoon motion pictures. The background drawings of the transmission line, scale lines, generator, and terminal connection in the animation scenes were made on celluloid. These were then printed photographically on film to avoid trouble due to chipping off the ink, which occurred when the original drawings on transparent celluloid were used repeatedly. Transparencies were used also in obtaining a number of special effects, including rotating commutators, closing switches, sections of wave moved and inverted to illustrate the action of complete reflection.

In order to economize on the labor required, the distribution plots were not made independently for each frame of the motion picture. One was made for every eighth frame, and the distributions in between were determined by graphical interpolation first into halves, then quarters, and finally eighths. One hundred twenty-eight different views were prepared to produce a transit of the wave from one end of the line to the other. As the steady state was approached and the motion became very slow, it was found possible to use one distribution diagram

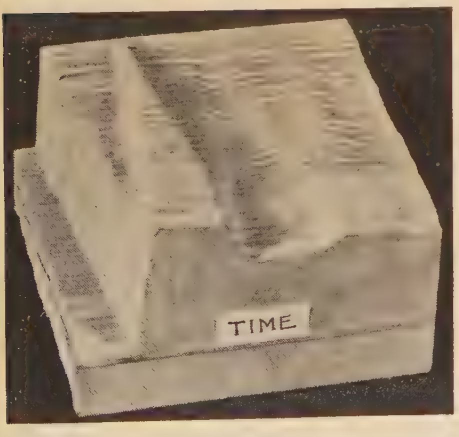


Figure 5. Direct-voltage switching transient on line loaded with resistance greater than surge impedance

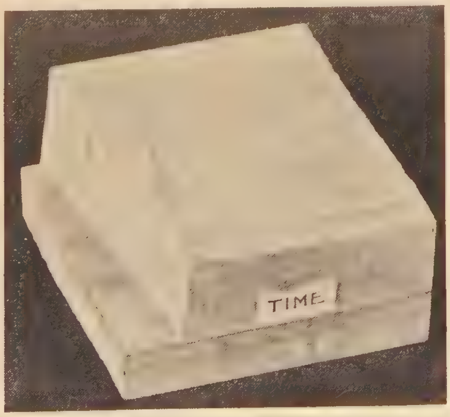


Figure 6. Direct-voltage switching transient on line loaded with resistance equal to surge impedance

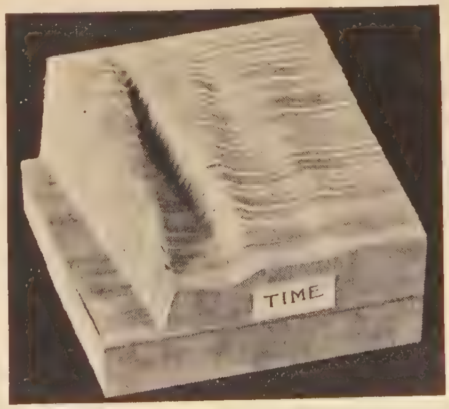


Figure 7. Direct-voltage switching transient on line loaded with resistance less than surge impedance

for two or more successive exposures on the film, without producing an effect of jumpiness on the screen.

On the screen, the progress of the wave is shown in slow motion, its time of propagation on the 250-mile line being increased from one seven-hundred-fiftieth second to about ten seconds. The actual linear speed on the screen is made about *one billionth* of the actual speed.

Direct-Voltage Waves on Short-Circuited Line

The second case treated was that of direct-voltage waves on a short-circuited line. The solid figure showing the voltage-time-distance variation is pictured in figure 3. A number of the voltage distributions along the line are shown in figure 4.

Combined with the depicting of the building up of the voltage on the short-circuited line, there was shown also the process of draining this charge from the line by switching off the generator and allowing the line to discharge through a noninductive resistance equal numerically to the surge impedance of the line.

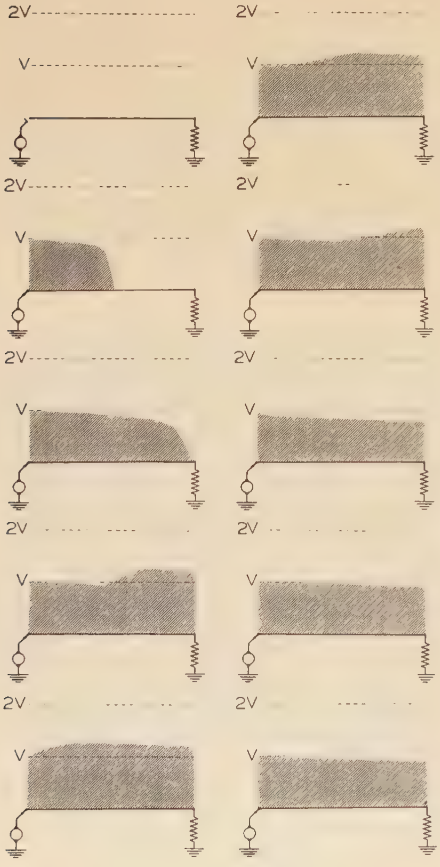
Direct-Voltage Waves on Line With Resistance Load

Three cases of resistance load were treated in order to bring out the different types of partial reflection. These were for values of load resistance greater than, equal to, and less than the surge impedance of the line. The solid figures of voltage-time-distance variation are shown in figures 5, 6, and 7. Distributions of voltage are shown in figures 8 and 9. It may be observed in figure 8 that partial reflections without a change of sign occur at a resistor termination whose resistance is greater than the surge impedance. No reflection occurs when the termination has a noninductive resistance equal to the surge impedance. Partial reflections with change of sign are shown in figure 9, which is for the line with termination having noninductive resistance less than the surge impedance.

Direct-Voltage Waves on Line With Inductive Load

The case of voltage waves striking an inductive termination was treated. The three-dimensional plot, made by packing together 33 oscillograms pasted on plywood and cut out along the curves, is pictured in figure 10. Plots of voltage distribution are shown in figure 11.

It may be observed that when the voltage wave first strikes the inductive load, there is an approximately complete reflection without a change of sign, just as is the case when the wave strikes an open end. The reason for this is that the flow of current along the line accompanying this voltage wave is temporarily halted by the inductance. In order for the current to flow on without delay into the inductance, an infinite rate of change of current there would be required, if there were no distributed capacitance in the inductor itself. The rate of change of current build-up can occur only at a rate such that the back emf produced by the inductance will equal the voltage impressed on the inductance. This initial stoppage of the current causes the charge to build up just as in the open-line case, but soon the current begins to flow in appreciable



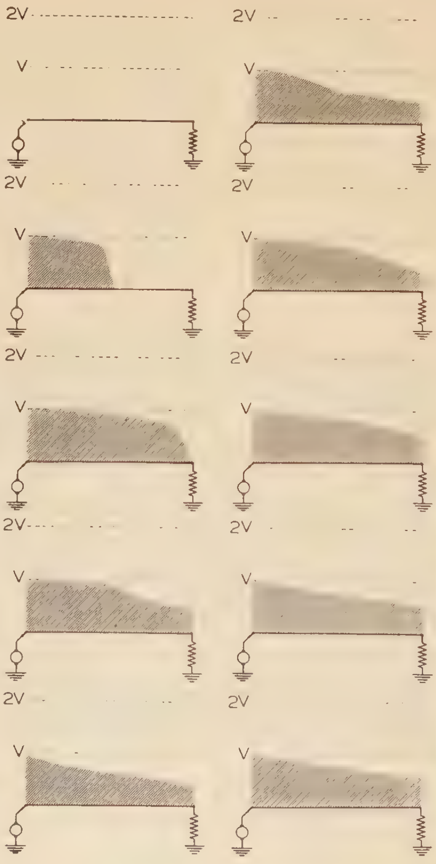
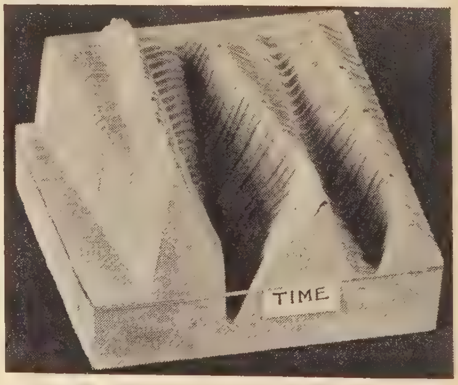


Figure 8 (extreme left). Direct-voltage waves on line loaded with resistance greater than surge impedance

Figure 9 (left). Direct-voltage waves on line loaded with resistance less than surge impedance

Figure 10 (below). Direct-voltage switching transient on line with inductive load



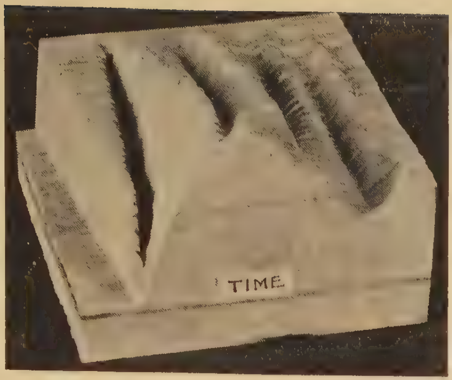


Figure 12 (above). Direct-voltage switching transient on line with capacitive load

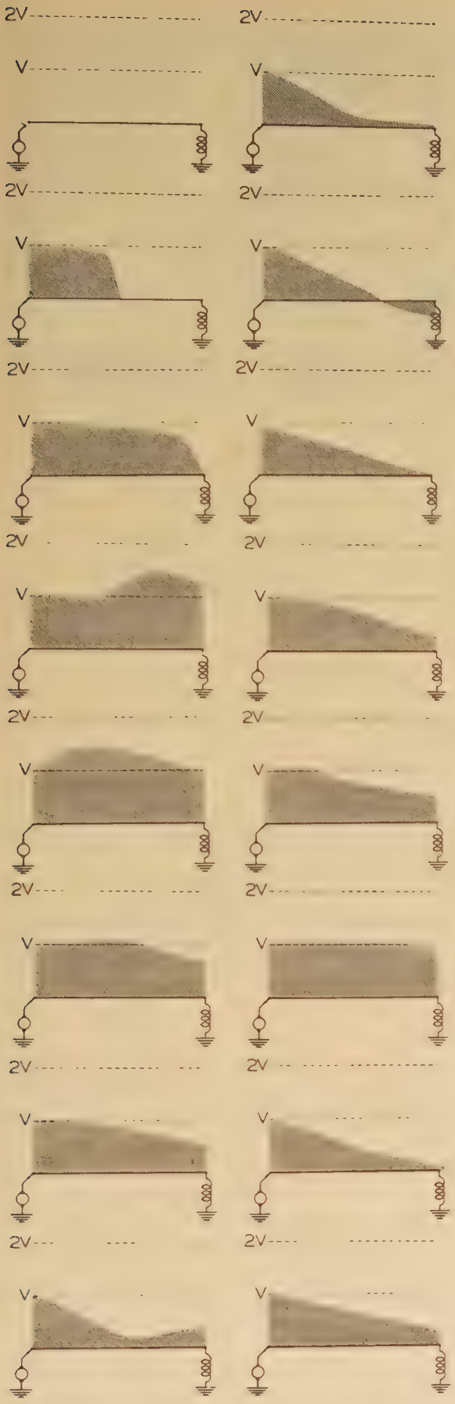


Figure 11 (left). Direct-voltage waves on line with inductive load

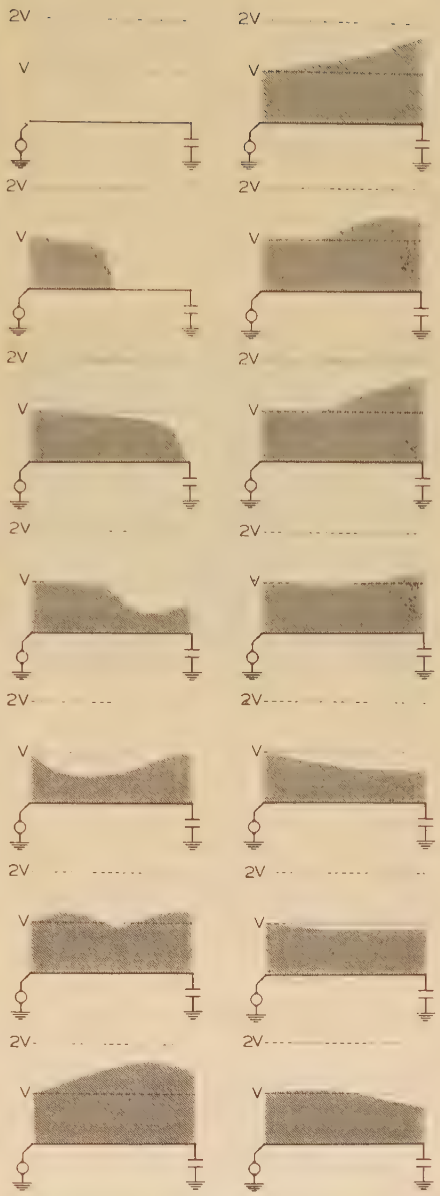


Figure 13 (right). Direct-voltage waves on line with capacitive load

quantity through the inductance, draining some of the charge off the line and reducing the voltage. The size of the inductance used as a load in these tests was approximately the same as that of the entire 250 miles of line—about one henry.

When the original wave has reflected from the load, and the reflection returned to the sending end, its sign becomes reversed, and when it travels down toward the load end again, its sign is negative. This negative wave reaches the load and undergoes a negative reflection, at a time when the voltage at and near the load has been greatly reduced by the continuously increasing current which is being drained away by the inductive load. As a result, the net voltage at the load and near it goes below zero and takes on a very considerable negative value.

Direct-Voltage Waves on Line With Capacitive Load

Another case treated was that of direct-voltage waves on a line with a termination of capacitance. The solid figure of voltage-time-distance variation for this case is shown in figure 12; and plots of distribution at different instants of time in figure 13. It will be observed that the initial reflection is similar to that on a short-circuited line, since the load end is maintained at zero voltage until a finite and sufficient time has elapsed to allow a finite quantity of charge to accumulate in the condenser. The action as this charge accumulates can be traced by the rise of the voltage behind the wave front of the first reflection as it makes its way back toward the sending end.

Alternating-Voltage Waves

No motion pictures have been made as yet of the alternating-voltage waves. It was felt that the comparative simplicity of the d-c phenomena made the d-c case more valuable for illustrating fundamental phenomena. Another reason for the choice was the fact that for most power lines the wave phenomena take place and are completed so rapidly that there is usually very little change in the instantaneous value of impressed voltage during the interval.

However, oscillograms were taken for a number of a-c cases, and three-dimensional figures built up as before.

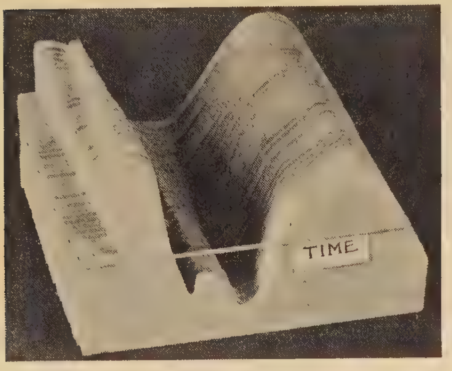


Figure 14. Alternating - voltage switching transient on open line

In figure 14 is shown the voltage-time-distance relation on a 250-mile open line when a 60-cycle-per-second voltage is suddenly impressed at the peak of its wave.

In figure 15 is shown another solid plot for the a-c case, which differs from that of figure 14 only in that the line was loaded with a resistance equal to approximately twice the surge impedance of the line, instead of being open.

Possibility of Further Work

It is questionable just how far treatment of different types of wave should be carried, owing to the very considerable amount of expense, time, and effort involved. It is felt, however, that the effort expended on the films so far produced has been well invested.

Additional oscillographic data have been taken of waves on a large lead-covered telephone cable which was generously lent for the purpose by Bell Telephone Laboratories, Inc. Tests were made without loading and with loading coils at the usual intervals, for direct current and for 1,000-cycles-per-second alternating current impressed. These data are in form sufficiently complete to form the basis for a number of traveling-wave films showing telephone-transmission phenomena, if they should be undertaken in the future.

If these films were to be made for the a-c case it appears that the best method of procedure in the preparation of the master distribution diagrams would be to work from the d-c distributions by applying the superposition formula,[4] using a mechanical method of integration. By doing this, various frequencies may be treated, as may the impressing of the voltage at different parts of the cycle, and even complex waves representing speech. Voltages of two widely separated frequencies, superposed and traveling along the line, would illustrate effects of amplitude and phase distortion.

It would undoubtedly be most interesting to see films of waves produced by lightning on power lines, showing the effect of corona and of lightning arrester operation. Perhaps at some future time they may be made.

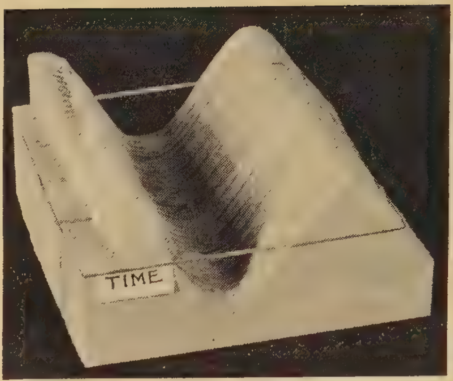


Figure 15. Alternating - voltage switching transient on line loaded with resistance greater than surge impedance

Grateful acknowledgment is made to Messrs. Frank H. Conant, Philip H. Ramsdell, and B. E. Battit for their parts in the work.

Appendix—Computed Voltage Wave

It was desired for comparative purposes to show a voltage wave computed on the basis of assumed constant line parameters, as already stated. The literature was searched for the best and most practicable formulas to use in the computation.

J. R. Carson[4] gives an integral formula for the voltage as a function of x and t, on a line with uniformly distributed and constant resistance R, inductance L, and capacitance C (leakage zero) per unit length, as follows:

$e(x,t) = 0$ for $vt < x$.

For $vt \geq x$,

$$e(x,t) = E\epsilon^{-A} + EA\int_A^T \frac{\epsilon^{-T_1} \cdot I_1(\sqrt{T_1^2 - A^2})}{\sqrt{T_1^2 - A^2}}\, dT_1$$

where

$$A = \frac{R}{2}\sqrt{\frac{C}{L}}\, x$$

$$T = \frac{R}{2L}\, t$$

$$v = \frac{1}{\sqrt{LC}} = \text{velocity of propagation}$$

E = size of suddenly impressed d-c voltage

V. Bush[5] gives the following solution, following Heaviside[6]:

$$e(x,t) = E\epsilon^{-\rho t}\left[1 + \left(\frac{x\sigma^2}{2v} + \rho\right)\left(t - \frac{x}{v}\right) + \left(\frac{x^2\sigma^4}{2^2 2!^2 v^2} + \frac{x\sigma^2\rho}{2^2 v} + \frac{\rho^2}{2!}\right)\left(t - \frac{x}{v}\right)^2 + \dots\right]$$

noting that it is useful for computation only when $(t - x/v)$ is small. In the above, the new symbols have the following definitions:

$$\rho = \frac{R}{2L} + \frac{G}{2C}$$

$$\sigma = \frac{R}{2L} - \frac{G}{2C}$$

It may be noted that when the leakage G is equal to zero, $\rho = \sigma = R/2L$.

Now a fairly simple formula is available for the computation of the *current* wave on a nonleaky line, and in view of the simplicity of the relation which exists between current and voltage, it was decided to attempt to determine the voltage by performing the necessary operations on the known current solution.

We have from Heaviside and may later writers the current-wave formula for the nonleaky line, as follows, for $x \lesssim vt$:

$$i = E\sqrt{\frac{C}{L}}\,\epsilon^{-\frac{Rt}{2L}}\,I_0\left[\frac{R}{2L}\sqrt{t^2-\frac{x^2}{v^2}}\right] \tag{1}$$

In equation 1 I_0 designates the Bessel function of the first kind and zero order, for pure imaginary argument. Let the abbreviation Z be introduced, equal to

$$Z = \frac{R}{2L}\sqrt{t^2-\frac{x^2}{v^2}} = \frac{R}{2Lv}\sqrt{(vt-x)(vt+x)} \tag{2}$$

so that (1) simplifies to

$$i = E\sqrt{\frac{C}{L}}\,\epsilon^{-\frac{Rt}{2L}}\,I_0(Z) \tag{3}$$

One of the fundamental differential equations upon which transmission-line wave solutions are based is, for zero leakage,

$$\frac{\partial e}{\partial t} = -\frac{1}{C}\frac{\partial i}{\partial x} \tag{4}$$

The value of i given in equation 3 will be substituted into equation 4, and then solution for e will be made. Throughout the following, it is assumed that $0 < x < vt$. It is known of course that for $x > vt$ the voltage $e = 0$. It is assumed that we are dealing with an infinite line, although of course this solution is applicable to finite lines by proper handling of the reflections.

$$\frac{\partial Z}{\partial x} = -\frac{R^2x}{4L^2v^2Z} \tag{5}$$

$$\frac{\partial Z}{\partial t} = \frac{R^2t}{4L^2Z} \tag{6}$$

From (3), (4), and (5),

$$\frac{\partial e}{\partial t} = E\,v\epsilon^{-\frac{Rt}{2L}}\,\frac{\partial I_0(Z)}{\partial Z}\cdot\frac{R^2x}{4L^2v^2Z} \tag{7}$$

We have the following recurrence formula[7] for Bessel functions:

$$\begin{aligned}\frac{\partial I_n(Z)}{\partial Z} &= \frac{nI_n(Z)}{Z} + I_{n+1}(Z)\\ &= I_{n-1}(Z) - \frac{nI_n(Z)}{Z}\end{aligned} \tag{8}$$

From the resemblance which equation 7 bears to $\partial i/\partial t$ it can be seen that by adding and subtracting the quantities in the brackets below, a portion of the expression can be made a perfect differential with respect to t.

$$\begin{aligned}\frac{\partial e}{\partial t} &= E\epsilon^{-\frac{Rt}{2L}}\frac{\partial I_0(Z)}{\partial Z}\,\frac{R^2x}{4L^2vZ} + E\Bigg[\epsilon^{-\frac{Rt}{2L}}\frac{\partial I_0(Z)}{\partial Z}\,\frac{R^2(vt-x)}{4L^2vZ} - {}\\ &\quad \epsilon^{-\frac{Rt}{2L}}\frac{\partial I_0(Z)}{\partial (Z)}\,\frac{R}{2L}\sqrt{\frac{vt-x}{vt+x}} + \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}}I_0(Z) - \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}}I_0(Z)\Bigg]\\ &= E\left[\epsilon^{-\frac{Rt}{2L}}\frac{\partial I_0(Z)}{\partial Z}\,\frac{R^2t}{4L^2Z} - \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}}I_0(Z)\right] - {}\\ &\qquad E\epsilon^{-\frac{Rt}{2L}}\frac{\partial I_0(Z)}{\partial Z}\,\frac{R}{2L}\sqrt{\frac{vt-x}{vt+x}} + E\frac{R}{2L}\epsilon^{-\frac{Rt}{2L}}I_0(Z)\end{aligned} \tag{9}$$

By the recurrence formula, equation 8, it is seen that $\partial I_0(Z)/\partial Z$ in the second term of equation 9 may be replaced by $I_1(Z)$. We have further the general relation that

$$\int u\,v\,dw = u\,v\,w - \int u\,w\,dv - \int v\,w\,du \tag{10}$$

which it is convenient to apply to this same second term, with

$$u = \frac{\partial I_0(Z)}{\partial Z} \text{ or } I_1(Z)$$

$$v = \sqrt{\frac{vt-x}{vt+x}}$$

$$dw = -\frac{R}{2L}\epsilon^{-\frac{Rt}{2L}}\,dt$$

The entire expression for $\frac{\partial e}{\partial t}$ is then integrated with respect to t, giving:

$$\begin{aligned}e &= f(x) + E\epsilon^{-\frac{Rt}{2L}}I_0(Z) + E\epsilon^{-\frac{Rt}{2L}}I_1(Z)\sqrt{\frac{vt-x}{vt+x}} + {}\\ &\quad E\int\Bigg\{-\epsilon^{-\frac{Rt}{2L}}\frac{\partial I_1(Z)}{\partial Z}\,\frac{R^2t}{4L^2Z}\sqrt{\frac{vt-x}{vt+x}} - \epsilon^{-\frac{Rt}{2L}}I_1(Z)\,\frac{vx}{(vt+x)^2}\times\\ &\qquad\qquad \sqrt{\frac{vt+x}{vt-x}} + \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}}I_0(Z)\Bigg\}dt\end{aligned} \tag{11}$$

Using the recurrence formula (8) again and substituting for $\partial I_1(Z)/\partial Z$ and $I_0(Z)$ there results, for the integral term:

$$\begin{aligned}e &= \ldots\ldots + E\int\Bigg\{-\epsilon^{-\frac{Rt}{2L}}I_1(Z)\,\frac{R^2t}{4L^2Z^2}\sqrt{\frac{vt-x}{vt+x}} - {}\\ &\quad \epsilon^{-\frac{Rt}{2L}}I_2(Z)\,\frac{R^2t}{4L^2Z}\sqrt{\frac{vt-x}{vt+x}} - \epsilon^{-\frac{Rt}{2L}}I_1(Z)\,\frac{vx}{(vt+x)^2}\sqrt{\frac{vt+x}{vt-x}} + {}\\ &\qquad \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}}\left[I_2(Z) + \frac{2I_1(Z)}{Z}\right]\Bigg\}dt\end{aligned} \tag{12}$$

Substituting in (12) the value of Z from (2), and simplifying, there results:

$$\begin{aligned}e &= \ldots\ldots + E\int\Bigg\{-\epsilon^{-\frac{Rt}{2L}}I_1(Z)\left[\frac{v^2t}{(vt+x)^{3/2}(vt-x)^{1/2}} + {}\right.\\ &\quad \left.\frac{vx}{(vt+x)^{3/2}(vt-x)^{1/2}} - \frac{2v}{(vt+x)^{1/2}(vt-x)^{1/2}}\right] + {}\\ &\qquad \epsilon^{-\frac{Rt}{2L}}I_2(Z)\left[\frac{R}{2L} - \frac{R\,vt}{2L(vt+x)}\right]\Bigg\}dt\end{aligned} \tag{13}$$

The first two terms of the first bracket in (13) have a common denominator, and together they equal half the negative value of the third term. These terms come from the term in equation 11 containing $\partial I_1(Z)/\partial Z$ and the succeeding term. If the signs of these terms in (11) are reversed, the result is a doubling of the two terms referred to in (13), which will cause the entire first bracketed expression to become zero. In order to compensate for this change in sign, we must add

$$E\epsilon^{-\frac{Rt}{2L}}I_1(Z)\sqrt{\frac{vt-x}{vt+x}}$$

to the integral portion of e, as may be seen by inspection of (10) and

(11). We then have:

$$e = f(x) + E\epsilon^{-\frac{Rt}{2L}} I_0(Z) + 2E\epsilon^{-\frac{Rt}{2L}} I_1(Z) \sqrt{\frac{vt - x}{vt + x}} +$$

$$E\int \left\{ \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}} I_2(Z) \left[1 - \frac{2vt}{vt + x}\right] + \epsilon^{-\frac{Rt}{2L}} \frac{\partial I_0(Z)}{\partial Z} \frac{R}{2L} \sqrt{\frac{vt - x}{vt + x}} \right\} dt$$

$$= \ldots + E\int \left\{ -\frac{R}{2L}\epsilon^{-\frac{Rt}{2L}} \left(\frac{vt - x}{vt + x}\right) I_2(Z) + \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}} \sqrt{\frac{vt - x}{vt + x}} I_2(Z) \; dt \right. \quad (14)$$

Now we may take the integral term at the end of equation 14 and operate upon it in a manner similar to that used in integrating and reducing the last two terms of equation 9. There results:

$$E\int \left\{ -\frac{R}{2L}\epsilon^{-\frac{Rt}{2L}} \left(\frac{vt - x}{vt + x}\right) I_2(Z) + \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}} \sqrt{\frac{vt - x}{vt + x}} I_1(Z) \right\} dt =$$

$$2E^{-\frac{Rt}{2L}} \left(\frac{vt - x}{vt + x}\right) I_2(Z) + E\int \left\{ -\frac{R}{2L}\epsilon^{-\frac{Rt}{2L}} \left(\frac{vt - x}{vt + x}\right)^{3/2} I_3(Z) + \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}} \left(\frac{vt - x}{vt + x}\right) I_2(Z) \right\} dt \quad (15)$$

It is seen that each integration results in another integral of the same character but of order one higher, and a by-product of an additional term outside the integral. The evaluation of the integral may be generalized for the nth term as follows:

$$E\int \left(\frac{vt - x}{vt + x}\right)^{n/2} \frac{R}{2L}\epsilon^{-\frac{Rt}{2L}} \left[-I_{n+1}(Z) \left(\frac{vt - x}{vt + x}\right)^{1/2} + I_n(Z) \right] dt =$$

$$2E\epsilon^{-\frac{Rt}{2L}} \left(\frac{vt - x}{vt + x}\right)^{\frac{n+1}{2}} I_{n+1}(Z) + E\int \left(\frac{vt - x}{vt + x}\right)^{\frac{n+1}{2}} \times \frac{R\epsilon^{-\frac{Rt}{2L}}}{2L} \left[-I_{n+2}(Z) \left(\frac{vt - x}{vt + x}\right)^{1/2} + I_{n+1}(Z) \right] dt \quad (16)$$

The relation expressed in (16) was obtained by induction, but a direct proof of it may be had by differentiating it with respect to t.

The voltage wave may be expressed:

$$e(x, t) = f(x) + E\epsilon^{-\frac{Rt}{2L}} I_0(Z) + 2E\epsilon^{-\frac{Rt}{2L}} \sum_{n=1}^{\infty} I_n(Z) \left(\frac{vt - x}{vt + x}\right)^{n/2} \quad (17)$$

If the line is initially uncharged, $f(x)$ is equal to zero. There is a discontinuity at $x = vt$, and equation 17 indicates a wave front (which exists where this condition holds) of magnitude

$$E\epsilon^{-\frac{Rt}{2L}}$$

The magnitude of the current wave front, found by substituting $x = vt$ in equation 3, is

$$E\sqrt{C/L}\,\epsilon^{-\frac{Rt}{2L}}$$

The wave front is advancing at a velocity $v = 1/\sqrt{LC}$, and it is seen that this flow of current is just sufficient to charge up the line at this rate and to the magnitude indicated as being required by the expression for the voltage wave front. The voltage solution is therefore compatible with the current solution at the point of discontinuity.

For $x > vt$, the voltage is everywhere zero, since no charge has yet been brought to that part of the line by the oncoming current wave.

Let the new symbol s be introduced, defined as:

$$s = \sqrt{\frac{vt - x}{vt + x}} \quad (18)$$

Then the expression for the original voltage wave, due to a direct voltage E suddenly impressed on a transmission line with constants R, L, and C, is:

$$e = E\epsilon^{-\frac{Rt}{2L}} \{I_0(Z) + 2sI_1(Z) + 2s^2I_2(Z) + 2s^3I_3(Z) + \ldots)\} \quad (19)$$

where

$$I_n(Z) = \frac{Z^n}{2^n n!} \left\{ 1 + \frac{Z^2}{2^2 1!(n + 1)} + \frac{Z^4}{2^4 2!(n + 1)(n + 2)} + \ldots \right\} \quad (20)$$

In a similar manner, the more complicated case of the line with all four constants R, L, C, and G may be worked out in terms of Bessel functions. The result is:

$$\begin{aligned} e = {} & E\epsilon^{-\rho t}\{I_0(Z) + 2rsI_1(Z) + (4r^2 - 2)s^2I_2(Z) + \\ & (8r^3 - 6r)s^3I_3(Z) + (16r^4 - 16r^2 + 2)s^4I_4(Z) + \\ & (32r^5 - 40r^3 + 10r)s^5I_5(Z) + (64r^6 - 96r^4 + 36r^2 - 2)s^6I_6(Z) + \\ & (128r^7 - 224r^5 + 112r^3 - 14r)s^7I_7(Z) + \\ & (256r^8 - 512r^6 + 320r^4 - 64r^2 + 2)s^8I_8(Z) + \ldots.\} \end{aligned} \quad (21)$$

In the above, the symbols have all already been defined except r, which is defined as $\frac{\rho}{\sigma}$, and Z is made equal to

$$\sigma\sqrt{t^2 - \frac{x^2}{v^2}}$$

Equation 19 is the one which was used in the computation of the voltage distributions for the motion picture.

A table of Bessel functions of orders from 0 to 11, and covering the range of argument required, is available in the Report of the British Association for 1896.

In the artificial line used, which was made up of 32 sections of the single-phase line described in Dellenbaugh's paper,[2] the constants were:

	Per Section	32 Sections
Resistance	7.9 ohms	252.8 ohms
Inductance	0.0326 henry	1.043 henries
Capacitance	0.0565 microfarad	1.808 microfarads
Equivalent length	7.87 miles	251.84 miles

The computation for voltage distribution was carried out for a range of x and vt between 0 and 12 times the length of the line (0 and 384 sections), at intervals of one quarter of the length or eight sections. A few of the early results are given in table I, which is reproduced only in small part on account of the large size of the complete table.

For the open-line case, the reflection from the end is complete and without change of sign. To illustrate the numerical computation, let vt = 40 sections, or one and one-fourth times the length of line. Then the section of the wave indicated in table I as lying between x = 32 and x = 40 has actually turned around and gone back from 32 to 24. The wave front is at section 24 and moving toward the generator. The distribution is

x(section) =	0	8	16	24	32
e/E =	1.000	0.962	0.925	0.887 1.699	1.700

The first three figures and the upper figure under section 24 are

Table I. Values of Computed Voltage e(x,t) per Volt Impressed

vt (Sections) \ x (Sections)	0	8	16	24	32	40	48
0	1.000	0	0	0	0	0	0
8	1.000	0.959	0	0	0	0	0
16	1.000	0.960	0.920	0	0	0	0
24	1.000	0.9605	0.921	0.883	0	0	0
32	1.000	0.9613	0.923	0.885	0.847	0	0
40	1.000	0.962	0.925	0.887	0.850	0.812	0
48	1.000	0.963	0.926	0.889	0.852	0.816	0.779

taken directly from table I. The other entry under section 24 is the sum of the table I entries for sections 24 and 40. The entry under section 32 is twice the corresponding entry in table I. The two entries under section 24 represent the values of the wave at the top and bottom of the wave front there.

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Discussion

John Riordan (nonmember; Bell Telephone Laboratories, Inc., New York, N. Y.): I wish to present a verification of the expansion given as equation 21 in the appendix to Mr. Woodruff's paper; this is the general result of the development in the appendix. I should explain at once that the process I use is not a substitute for Mr. Woodruff's original method; given the form of the expansion by Mr. Woodruff, it will determine the coefficients and verify the form, but it requires either this advance information or an act of inspiration to be complete. However, I am able by its means to give a generating function, a literal formula, and a recurrence formula for the coefficients of the general expansion, equation 21, thus completing Mr. Woodruff's work. The coefficients turn out to be simply related to the Tchebycheff polynomials.

Using the notation of the paper with a slight modification, the expansion to be verified is as follows:

$$e = E\sum_{n=0}^{\infty} C_n(r)s^n I_n(\sigma z)\exp(-\rho t)$$

where

$C_n(r)$ = function of r and n which is the coefficient of the nth term in equation 21.

$r = \rho/\sigma$

$z = [t^2 - x^2/v^2]^{1/2}$

Using the Campbell and Foster table of Fourier integrals (Bell Telephone System Technical Publications, Monograph *B*-584), by pair 870.5:

$$\mathfrak{M}[s^n I_n(\sigma z)\exp(-\rho t)] = \frac{(2\sigma)^n \exp\left[\dfrac{-x}{v}\sqrt{(p+\rho)^2-\sigma^2}\right]}{\sqrt{(p+\rho)^2-\sigma^2}\,[\sqrt{p+\rho+\sigma}+\sqrt{p+\rho-\sigma}]^{2n}}$$

where the script $\mathfrak{M}$ is to be read "mate of" or "Fourier transform of."

Hence the original expansion may be written

$$\mathfrak{M}(e) = E\,\frac{\exp\left[\dfrac{-x}{v}\sqrt{(p+\rho)^2-\sigma^2}\right]}{\sqrt{(p+\rho)^2-\sigma^2}}\sum_{n=0}^{\infty} C_n(r)u^n$$

where

$$u = \frac{2\sigma}{[\sqrt{p+\rho+\sigma}+\sqrt{p+\rho-\sigma}]^2} = \frac{\sigma}{p+\rho+\sqrt{(p+\rho)^2-\sigma^2}}$$

But the mate of e is known otherwise (Campbell and Foster, l.c. table II, case 3) as:

$$\mathfrak{M}(e) = \frac{E}{p}\exp\left[\frac{-x}{v}\sqrt{(p+\rho)^2-\sigma^2}\right]$$

Hence $C_n(r)$ is determined, assuming the form of the expansion is correct, by:

$$\sum_{n=0}^{\infty} C_n(r)u^n = \frac{\sqrt{(p+\rho)^2-\sigma^2}}{p}$$

If the right-hand side may be expressed as a function of u and r the expansion is correct and the expression so obtained is the generating function of $C_n(r)$. Writing $W = \sqrt{(p+\rho)^2 - \sigma^2}$, for convenience, this may be done as follows:

$$\begin{aligned}\frac{W}{p} &= \frac{W(p+W)}{p(p+W)}\\ &= \frac{p(p+W)+2\rho p+\rho^2-\sigma^2}{p(p+W)}\\ &= 1+\frac{2\rho}{p+W}+\frac{(\rho^2-\sigma^2)(p+W)}{p(p+W)^2}\\ &= 1+\frac{2\rho}{p+W}+\frac{\rho^2-\sigma^2}{(p+W)^2}+\frac{W}{p}\,\frac{\rho^2-\sigma^2}{(p+W)^2}\end{aligned}$$

Hence, noting that $p + W = -\rho + \sigma/u$:

$$\frac{W}{p}\left[1+\frac{(1-r^2)u^2}{(1-ru)^2}\right] = 1+\frac{2ru}{1-ru}-\frac{(1-r^2)u^2}{(1-ru)^2}$$

or

$$\frac{W}{p} = \frac{1-u^2}{1-2ru+u^2}$$

which is the required generating function expression.

But the Tchebycheff polynomials $T_n(r)$ (Courant and Hilbert, Methoden der Math. Physik, Springer, Berlin, 1931, pages 75 and 76) defined by

$$T_n(r) = \frac{1}{2^{n-1}}\cos[n\cos^{-1}r]$$

have the generating identity:

$$\frac{1-x^2}{1-2rx+x^2} = \sum_{n=0}^{\infty} T_n(r)(2x)^n$$

Hence

$$C_n(r) = 2^n T_n(r) = 2\cos[n\cos^{-1}r]$$

and for $n \geq 2$:

$$T_{n+1}(r) = rT_n(r) - \frac{1}{4}T_{n-1}(x)$$

$$C_{n+1}(r) = 2rC_n(r) - C_{n-1}(r)$$

the last of which is the recurrence relation for the coefficients. For convenience of comparison with Mr. Woodruff's result, the first few coefficients are as follows:

$$C_0(r) = 1$$
$$C_1(r) = 2r$$
$$C_2(r) = 4r^2 - 2$$
$$C_3(r) = 8r^3 - 6r$$

The first three follow from the literal formula, the last from the recurrence formula; they may also be obtained by simple long division development of the generating function.

In the special case $G = 0$, that is $\rho = \sigma$ and $r = 1$, the nth coefficient is

$$C_0(1) = 1$$

$$C_n(1) = 2\,n \mp 0$$

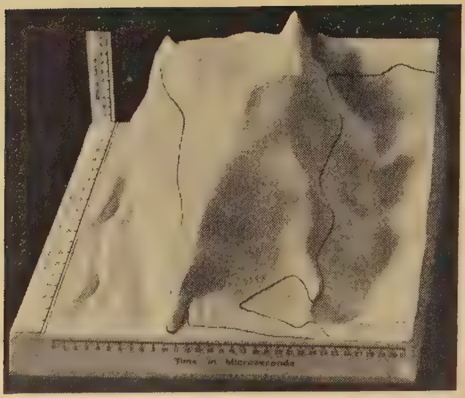
which verifies equation 19. This result follows immediately either from the generating function or the formula for $C_n(r)$.

I am indebted to my colleague S. O. Rice for pointing out the connection of the coefficients with the Tchebycheff polynomials.

L. V. Bewley (General Electric Company, Pittsfield, Mass.): Professor Woodruff has shown two very interesting and instructive methods of teaching transmission line transients by means of motion pictures and voltage-distance-time models. These should prove of great value to schools in which traveling wave phenomena is taught; because it gives the student a perfect visual picture of what is going on during the travel and reflection of a wave.

Along about 1929 we calculated the wave shapes for lightning surges and worked out the reflections for a number of terminal conditions, ("Traveling Waves Due to Lightning," AIEE TRANSACTIONS, volume 48, 1929). At that time F. W. Peek, Jr., was directing the lightning research at Pittsfield and he asked J. T. Lusignan, Jr., to supervise the making of an animated motion picture based on the calculated wave shapes. This film (General Electric *AX*-353-*B*) was shown by Mr. Peek before many different AIEE Sections throughout the country. It depicts the formation of a charged cloud; the lightning stroke; the formation and development of the traveling waves; the attenuation due to corona; reflections from open and grounded terminals and from a resistor equal to the surge impedance of the line, also from transformer terminals and series inductances with and without shunt resistors; and finally the internal transient oscillations taking place inside a transformer winding and their elimination by means of shields.

Figure 1



Several years ago D. C. Morgan at Pittsfield conceived the idea of illustrating the internal transient of a transformer by a topographical voltage-distance-time model, just as Professor Woodruff has now done for transmission lines. Figure 1 is a photograph of Morgan's plaster-cast model.

Discussions

of AIEE Technical Papers Published Before Discussions Were Available

ON THIS and the following 21 pages appear discussions submitted for publication, and approved by the technical committees, on previously published papers presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Alternator Short-Circuit Currents Under Unsymmetrical Terminal Conditions

Discussion of a paper by A. R. Miller and W. S. Weil, Jr., published on pages 1268–76 of volume 56, 1937, AIEE TRANSACTIONS (October 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 27, 1938.

F. H. Pumphrey (Rutgers University, New Brunswick, N. J.): I have been very much interested in the effort of Professor Miller and Mr. Weil to digest the work which has been done in machine transients and to present it in somewhat simpler form. The necessity of conforming with the Institute publication standards has prevented them from making a complete statement of assumptions. It thus becomes rather difficult to follow some of the steps and so the paper loses some of its advantage of completeness as well as simplicity.

In this connection, I have been unable to interpret physically the very low frequency element of armature current given on page 1269 I wonder if it might not be obtained equally accurately by a constant term with a different decrement? I should appreciate any help the authors could give on this interpretation.

Another question has arisen with respect to the change of resistance and reactance of the field circuit of the machine used as an illustration, between the first and second papers. Could the authors state the basis of this change?

D-C Machine Stray-Load-Loss Tests

Discussion and author's closure of a paper by Victor Siegfried published on pages 1285–9 of volume 56, 1937, AIEE TRANSACTIONS (October 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 27, 1938.

R. F. Franklin and **T. M. Linville** (General Electric Company, Schenectady, N. Y.): Stray-load losses of d-c machines are of particular interest to designers because by their reduction in value increased efficiency and decreased heating are obtained. Every effort, therefore, should be made to measure this loss as accurately as possible and to determine its manner of variation.

Designers have recognized the existence of stray-load loss for a number of years and many attempts have been made to evaluate its magnitude both by test and calculation. Unfortunately the nature of stray-load loss is such as to preclude its direct measurement. The usual method of measurement is to measure the total losses under load and from this measurement subtract all of the known losses which can be measured or calculated either directly or indirectly. This difference is called the *stray-load loss*. But some of the known losses cannot always be determined very accurately and vary in value from time to time. The errors thus introduced together with the inherent inaccuracies of testing methods, have lead to considerable difficulty in determining the stray-load loss.

Because of these difficulties, the AIEE Standards have devised a conventional segregated-loss method of evaluating these losses in which arbitrary methods of determining stray-load loss, brush-friction loss, brush-contact loss, and I^2R losses are given. These methods of determining these losses are, of course, to some degree in error, and attention was given to the possible error at the time the methods were devised. It is possible that with present better knowledge of these losses or possibly by some further investigation other methods could be devised that would give a more accurate determination of these losses in the majority of cases. It should be borne in mind, however, that the present method serves as a very practical and convenient method of determining individual losses which makes possible the approximate calculation of total losses without excessive cost to the trade.

On the other hand, it is also very desirable to have a more accurate method of determining these losses, even though the method may be more expensive and require more elaborate testing equipment. Such a method should prove of particular value to designers as the division of losses is of particular interest to them. It is probable that such a method would be too costly and impractical for general use. It would, however, afford a means of improving designs and furnishing data for a modification of the more convenient segregated-loss method which would make that method more accurate without increasing its cost and practicability. The booster-pump-back method described in these papers seems the most practical method yet devised. Its use is greatly handicapped by the requirement of duplicate units as it would be difficult to have machines calibrated for load loss available at all times. Nevertheless, an intensive study of this method in order to simplify the test procedure, find methods of increasing the accuracies of meter readings and reduce their number to a minimum and a determination of its limitations might be profitable. There are also certain inaccuracies in the determination of the various losses when using this method that should receive further study.

One of the most difficult losses to measure accurately is that of the brush losses. It is well established that the brush friction loss is sometimes reduced 50 per cent or more between no load and full load. Yet the brush friction loss is measured at no load and assumed to be the same under load. Because of this assumption the stray-load loss may actually measure negative at light values of load. It should, therefore, be recognized that under the present method of testing for stray-load loss that it contains a component of brush-friction even though this component may have a negative value.

Another loss that is difficult to measure is that of the brush-drop loss. Because of the uneven current distribution in the brush and the uncertainties of voltage measurements made on a moving commutator the actual brush-drop loss may be quite different from the loss measured. The difference between the two should be recognized as a component of stray-load loss.

A third uncertain loss measurement is that of the armature copper I^2R loss. This loss cannot be directly measured and so must be determined indirectly as accurately as possible. Since the magnitude of this loss is greatly influenced by the temperature of the armature winding, one of the problems is to accurately measure this temperature or else maintain it at the time the loss is measured. Either of these is difficult to accomplish and the inaccuracies introduced by the determination of this loss should also be recognized as a component of the stray-load loss.

The above discussion leads to the important conclusion that the stray-load loss cannot be measured without at the same time specifying how the other losses are to be determined. In those cases where the other losses cannot be accurately measured under the exact conditions of load at a given time, provision must be made to either measure them in a definite manner at no load under arbitrary conditions or to specify a definite manner for their calculation. In either case it should be recognized that any inaccuracies in the determination of any of the other losses will have an influence on the magnitude of the stray-load loss.

In analyzing the data given in the papers attention should be called to the distinction between the per cent stray-load-loss values given as compared to the one per cent stray-load loss specified in the AIEE Standards. The one per cent value is established in conjunction with the calculation of brush friction as a function of commutator speed, allowance of a definite value of volts brush drop and calculation of the armature I^2R loss at 75 degrees centigrade. The stray-load loss determined in the papers was not obtained in this manner. It is incorrect, therefore, to use the stray-load loss as measured in the papers as a basis for judging the conventional allowance of one per cent.

Commercially, only total losses are important and there should be little argument against the method of measuring the total losses described in the papers. Both papers recommend a booster for circulating current between the machines being tested. Unfortunately, the booster must carry the full current of the machines at a comparatively low voltage. Such a machine is not likely to be always available. It would be less expensive and more practical to adopt the conventional pump-back test as a sufficiently accurate determination of the total losses. This may be done entirely apart from a consideration of stray-load losses.

In conclusion, it appears that further study should be given to the measurement and calculation of the known as well as the stray-load losses. A better knowledge of these losses will not only be helpful to the designer in obtaining improved machines but will be helpful in increasing the accuracy of determining the total losses by the convenient segregated-loss method. The present papers show there is interest in the problem and have contributed valuable test data and presented improved methods of test. It is hoped further interest can be aroused in this subject so as to stimulate further investigation and progress.

E. W. Schilling (Michigan College of Mining and Technology, Houghton) and **R. J. W. Koopman** (University of Kansas, Lawrence): It is gratifying to know that at least one other party has answered the Institute's request that research work be started and papers presented on stray-load losses in d-c machines. Professor Siegfried has made tests using the so-called Kapp method and also using the Hutchinson test in which the two machines to be tested are direct connected and arranged in a pump-back connection using a booster to circulate the current. This last test is very similar to one of those used by us.

Referring to Professor Siegfried's figure 2, page 1286, ELECTRICAL ENGINEERING for October 1937 [AIEE TRANSACTIONS, volume 56] it is interesting to make a comparison of his method and our method of allocating the losses to the individual machines. Since we plot loss in watts as ordinates against average armature current as abscissae for the two machines, it is necessary to replot his curve A as shown in figure 1. Since his data plotted on logarithmic paper produces a straight line as shown in figure 2, the curve can be expressed by an equation of the form $L_s = kI_a^n$. The exponent is found to be 1.255. Now consider a point on his curve at 160 amperes. The distribution of current between the two machines is not given but for our purpose here we will consider $I_g = 75$ amperes and $I_m = 85$ amperes. The loss for one machine, at 75 amperes for example, will be

$$L_g = L_s \frac{I_g^n}{I_m^n+I_g^n} = 500 \frac{75^{1.255}}{85^{1.255}+75^{1.255}} = 242 \text{ watts at 75 amperes}$$

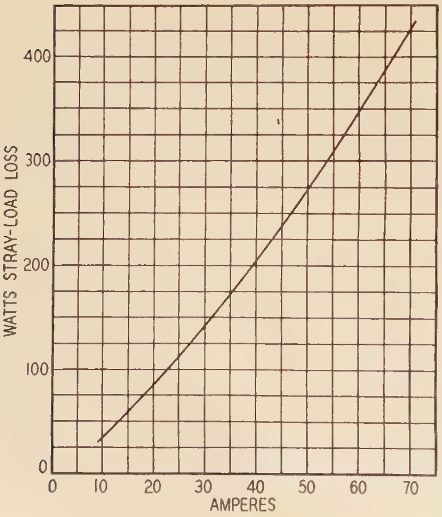


Figure 1. Curve A of Siegfried's figure 2 replotted to show average armature current for the two machines

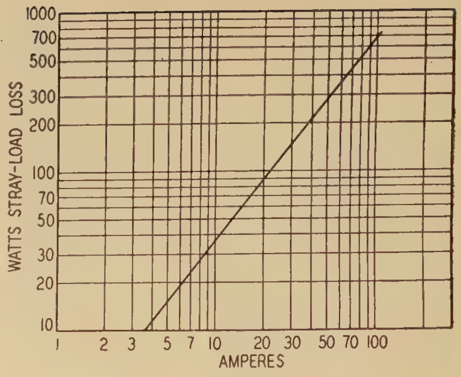


Figure 2. Determination of the exponent n

An interesting portion of Professor Siegfried's paper is the application of paraffin to the commutator to reduce friction loss. We can readily agree that some such procedure would be desirable, provided that the contact drop would be unaffected. However, it is hard to believe that such would be the case. Test data taken on slip rings with and without paraffin should be made to determine whether or not this very valuable aid to the technique of making stray-load loss tests may be safely used under all conditions.

In our tests brush drop was not taken at standstill. Contact drop measured at standstill will not under all conditions be the same as when the machine is running. The difference may be so small that it can safely be neglected. Contact drop curves taken at standstill and at various speeds should be valuable in determining whether this simplification in the test procedure can be used without too great loss of accuracy.

In the last paragraph of "Test of Machines," page 1288 of Professor Siegfried's paper, it appears that the no-load loss was measured when the two machines were running as motors taking the same armature current. The booster was then included in the circuit and the load current increased. A final reading was then taken of the no-load loss. The exact procedure followed here is not perfectly clear. According to the test code, paragraph, 2.112, the core loss shall be taken "when excited to produce a voltage at the terminals corresponding to the calculated internal voltage." We presume that this was the purpose of the second reading. However, if such was the case, what was the purpose of the first reading?

Edward Hughes (Technical College, Brighton, England): The results discussed in this paper are very useful in showing the close agreement between the Kapp and the Hutchinson methods. Their value, however, would have been greatly enhanced if the author had analyzed the reliable data collected from the various tests in a manner that would indicate the fundamental relationships between the stray loss and the factors which affect its magnitude. In a paper published in the *Journal* of the Institution of Electrical Engineers, volume 63, 1924, pages 35–50, I investigated the effect of flux distortion on iron loss by measuring the iron loss in an armature with its winding on open circuit, the flux being distorted by passing current through a compensating winding. Figure 3 shows the results obtained at 2,000 rpm. Similar curves were obtained for speeds varying between 200 and 2,400 rpm. It was found that over this range of speed and for cross ampere-turns varying between zero and those corresponding to full-load and for field excitation ranging from zero to about 50 per cent above the normal excitation, the total iron

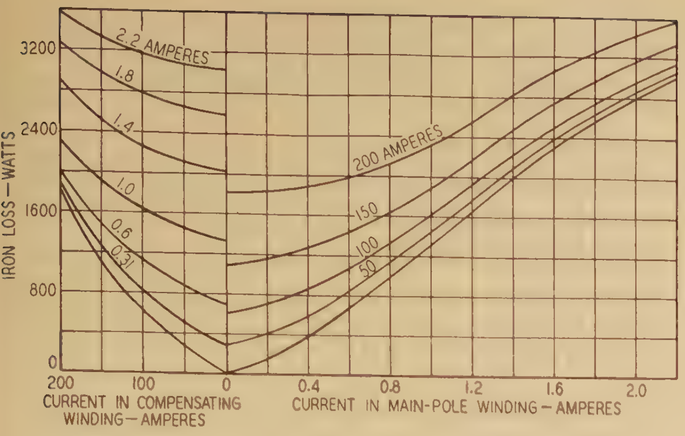


Figure 3

loss could be represented very closely by the following simple expression:

$$kf^{1.5}\{V_t(B_1^2 + B_2^2) + V_aB_a^2\}$$

where

k = a constant derived for undistorted flux
f = frequency in cycles per second
V_t = total volume of teeth
B_1 = mean flux density in tooth under strengthened pole tip
B_2 = ditto under pole tip at which the flux is reversed (if flux is not reversed, this term is omitted)
V_a = volume of armature core carrying flux
$B_a = \dfrac{\Phi + 2\Phi_c}{A}$
Φ = resultant flux per pole
Φ_c = cross flux (if any) re-entering pole shoe
A = sectional area per pole of magnetic circuit through armature core

The iron loss in armature teeth due to the flux of the commutating pole can be calculated from a similar formula.

The above expression has since been confirmed by R. G. Isaacs (*J.I.E.E.*, volume 69, page 1303). It is seen from the above expression that the stray iron loss is an integral part of the total iron loss. Consequently, if the stray loss is expressed as a separate quantity, it is impossible to relate it satisfactorily to the factors upon which it is dependent.

It is hardly necessary to emphasize that it is just as important to be able to predetermine the stray iron loss as it is to measure this loss after the machine has been constructed; and I would express the wish that the author should again analyze his results either to confirm the above expression or to suggest another that may fit in more satisfactorily with his own data.

T. H. Morgan (Worcester Polytechnic Institute, Worcester, Mass.): These papers are important and valuable in that they show that stray-load loss in d-c machines can be measured to a high degree of accuracy. The authors of both papers are to be complimented on their splendid painstaking work. Old and well-established methods are here applied to determine a loss which only recently has become recognized as one which cannot be ignored.

The results described in these papers indicate that we are well on our way in the matter of being able to definitely specify a simple straightforward method of determining stray-load loss in d-c machines. The load-back method is desirable because it gives a measurement of the loss with the machines under actual operating conditions. I am of the opinion that using boosters or other machines to supply certain losses separately and thus keep both machines under test in exactly similar conditions of load and field current is not necessary.

It is most desirable that a code method be as simple as possible without sacrificing the required degree of accuracy. It seems to me that these papers indicate that a test might be used in which one single voltage is applied to the machines operating in parallel on the same shaft with load conditions controlled by adjustment of the field currents. With this condition existing we would have the machines operating with slightly different armature currents and also with different field currents. The apportioning to each machine of the correct amount of its loss due to different armature currents can be conveniently and accurately taken care of by the method devised by Paul M. Narbutovskih for similar use in induction machines. If the law of variation of the stray-load loss as a function of saturation were sufficiently well established so that correct apportioning due to difference in field currents could be accomplished the problem would be solved and the whole matter of testing greatly simplified. The information given on this point in the papers would seem to indicate that for a given armature current the loss variation as a function of saturation might prove to be a very simple law throughout the range required for the test. Possibly the assumption of a straight line relationship would give the required degree of accuracy. Application of this law might be considerably simplified if one machine were over-excited to the same degree that the other was under-excited and the average excitation of the two similar machines used as the field current for this case. Further work along this line would be of great help in determining the accuracy of this proposal.

Coming back to the question of the test code I have never been able to understand a philosophy that says we will set up a code which will specify methods of testing for all the losses in a machine so that we may determine an accurate value of each, and then goes on to arbitrarily allot one loss as a fixed percentage of the input. I do not think that such procedure can be justified as being logical, scientific, or even practical, for in a matter of this kind practicality requires a fair degree of accuracy and not simply arbitrary action. It would seem that the authors of these papers have helped very materially by showing that it is possible to specify a definite method for the accurate measurement of stray-load loss in d-c machines.

L. E. Miller (Reliance Electric and Engineering Company, Cleveland, Ohio): I feel that Mr. Siegfried is to be complimented on the clearness of his paper. In view of the clearness and conciseness with which he has condensed the facts which might very easily cover many times the space of his paper, it seems like any discussion on the subject might be construed as near carping. I would like, however, to make some comments.

I believe that Mr. Siegfried has placed his finger upon the cause of considerable apparent inaccuracies which occur in many tests, when he attributed to the variability in the performance of the commutator. The very wide change in brush friction is very well brought out by Doctor S. W. Glass in his paper on "Measurement of Frictional Characteristics of Brushes," which was published in the July 1937 issue of *Iron and Steel.* Mr. Glass brings out in this article the possibility of a three-to-one change in brush friction for certain changes of temperature which are well within the range of a commutator temperature, and also a possibility of a variation as great as three-to-one occurring from sanding the commutator. He also brings out various rather wide ranges for various other phenomena which he classes as the effect of commutator poisons. In view of Doctor Glass' paper, I am forced to wonder as to whether it is not possible for paraffin, as mentioned by Mr. Siegfried, to cause certain inaccuracies which are not brought out into normal operation of the machine.

Siegfried also brings out the necessity of measuring the complete terminal to terminal drop, rather than assuming a constant value of brush contact drop. Presumably he makes this measurement while the machine is stationary. This brings up the question as to whether the stationary drop approaches any more closely the actual drop occurring while the machine is operating than the assumed value given under AIEE specifications. There is no doubt in my mind that the assumed value is inaccurate, but I question as to whether the stationary drop is not just as inaccurate.

Another point brought up in Mr. Siegfried's paper is the suggestion of leaving out series winding, which may be on the machine during these tests. Certainly the use of such a series winding does effect the field strength, and does vary as the load varies. On the other hand, I think it is quite possible to get inaccurate results when producing the same number of ampere turns in the shunt fields as the series field would produce under the conditions simulated. We have found in actual test that ampere turns from the shunt field do not produce the same resultant flux as ampere turns produced by the series field. The reason for this is no doubt due to the location of the shunt in series field on the pole and the differences in leakage resulting therefrom.

Mr. Siegfried very carefully points out the hysteresis effect that is noticeable and causes a different result when changing from a higher field current to a lower field current from that which is obtained when changing from a lower field current to a higher field current. I would like to add that on test floor we have also noticed what appears to be a hysteresis effect from changing the armature current. This is particularly noticeable under weak field conditions, and is probably due to the distorting action of the armature on the main field. I would suggest that in making a test of this sort where accuracy is very essential, that the tester be warned always to change the armature current in the same direction just previous to making readings.

Apparently from the results obtained by Mr. Siegfried the stray load loss is much greater at the high speed of an adjustable-speed motor where the high speed is obtained by weakening the field. From the curve shown it appears to be six or seven times as great as the full field low speed condition when operating at two and one-half times the low speed, and perhaps is ten to fifteen times as great on a four or five-to-one speed range operating at high speed. It is theoretically correct that we should get a much higher stray load loss at weak field and high speed than we should at full field and low speed. However, I would like to bring up for what it is worth, the fact that in making dynamometer tests, attempting to determine the difference in losses between those shown by the conventional method and the actual losses which are obtained in a machine, we have found that we could not establish any fixed rule for variation in the stray-load losses. The results were quite erratic, sometimes showing a greater stray-load loss at full field and low speed, sometimes showing a greater stray-load loss at the weakened field and highest speed, and sometimes showing a greater stray-load loss at some in-between value. These tests were made a year or more ago, and since the commutators were not treated in any way but were simply used in the condition existing at the time the tests were made, it is possible that the difference in commutator losses more than accounted for this erratic behavior.

I note in Mr. Siegfried's paper that he does not say anything regarding the possibility of shaft current causing part of the stray-load loss. I would like to inquire as to whether, during his test, he found any evidence of shaft current existing.

In closing, I would like to inquire as to whether Mr. Siegfried found any material difference in percentage of stray-load losses on larger machines than were present on smaller machines. In other words, is the present neglect of stray-load losses on smaller machines justified, or do the facts of the case show that this should be taken into account on smaller machines as well as on larger machines?

R. E. Hellmund (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): It is not at all surprising that close agreement on load losses has been obtained with the various methods discussed in the papers on this subject. Although the current and voltage conditions in the two machines on test differ to some extent with the simpler methods, the differences are not large enough to affect the results materially. It is nevertheless very gratifying to have the results of these careful investigations presented here, as any of the methods proposed can now be used with considerable confidence.

I am firmly convinced that most of the previous unsatisfactory results were due to variations caused by brush friction and perhaps, to a less extent, to variations in contact resistance. Since brush friction decreases with load and temperature, it may well be that in some machines the difference between brush friction at no load and at full load will be greater than the other load losses thus resulting in a negative value of load losses. A machine with a number of brushes, and having at the same time small armature distortion, well subdivided armature conductors, and good commutation, is likely to give such results.

Professor Siegfried has eliminated the irregularities often caused by brush friction by using paraffin on the commutators. This of course, is entirely satisfactory when analyzing the load losses other than those caused by brush friction and contact resistance. It would be helpful, however, if he could continue his work and make tests with the commutator in normal condition, being careful to obtain stable operation and temperature conditions as applying to no load, and also similar tests under full load. Care would also have to be taken that other factors of influence, such as humidity, are kept reasonably constant.

I was very much interested in the statement in the paper to the effect that current conduction between the brush and commutator through the paraffin film takes place because of carbon particles embedded in the film. In a previous discussion at last winter's convention, I suggested the possibility of such embedded particles being a factor with the usual oxide film on the commutator even under normal conditions. I am therefore wondering whether Professor Siegfried has any evidence supporting this theory, such as microscopic inspection for example.

Victor Siegfried: The author is indeed gratified by the interest shown in this subject, as evidence by the amount and the character of the discussion. It is apparent that the matter of stray-load loss in d-c machines is by no means a closed issue, and that much remains to be learned concerning its variation with the factors upon which it depends. The author is fully aware that many of the points touched upon in this paper and in its companion by Professors Schilling and Koopman, and by the discussers, show the need for further investigation of particular factors affecting stray-load loss. It must be made clear, however, that the author is here concerned primarily with establishing *methods* for determining the loss, and only secondarily with investigating the nature of the loss, in so far as it affects the procedure of the tests. It is shown by these papers that the loss can be measured accurately by a convenient and simple method, and that it is no longer necessary or proper to adopt an arbitrary percentage value to be assigned to it.

In considering matters relating to stray-load loss, it is very important that it be defined clearly. The definition given in the Test Code for D-C Machines is not sufficiently general, as it specifically mentions losses to be included, but does not allow for all factors which should be considered as a part of stray load loss. Stray-load loss is the difference between total losses as they occur under load conditions and the values of the individually known losses determined separately from measurements made under no-load conditions. It is thus a residual loss which includes all variations of machine losses under load which cannot otherwise be accounted for by conventional methods. It is made up of numerous component losses which change in differing degrees with load, in such a way as to preclude establishing any one general law for it.

The author is in complete agreement with Professor Morgan and Messrs. Franklin and Linville that the load-back test (without boosters) is the most practical and simplest method to be used. Although the two machines do operate thereby at different field currents, a division of the loss can be made, if the excitation is assumed to be represented by the average of the two machines, with reasonably accurate results over the normal range of excitations necessary for this test. For apportioning the loss between machines carrying different armature currents, the graphical separation method, devised by Mr. Narbutovskih and alluded to by Professor Morgan (1. Morgan and Narbutovskih, ELECTRICAL ENGINEERING, volume 53, 1934 pages 286–90) was used in this paper. As Professors Schilling and Koopman show, the results agree with their method, which involves the determination of the exponent of the function representing the total losses. It does not always follow that the exponent is constant over the entire range of currents in the machines, so that this method suffers from the limitation that the exponent must be determined in the range for which the separation is desired. The difference in methods is principally that between graphical and analytical approaches, as both perform the same operations upon the function; the choice is thus largely one of personal preference.

Mr. Hellmund points out the possibility of a decrease in brush friction with increasing values of load, and also that negative values of stray load loss may thus be indicated in certain instances. Such results must be interpreted in the light of the general definition of the loss, and in no way be allowed to reflect on the validity of the test. It was with full appreciation of the extreme variability of brush performance that the expedient of paraffining the commutator was adopted in making these tests, and it must be admitted that the results do not include any consideration of the possible decrease in this so-called constant no-load loss. Such procedure was permissible under the Test Code definition of stray load loss, which did not allow for any such variation. The comparison of methods as presented in the paper, and the general relations of stray load loss to operating factors, are in no way rendered less valid by this procedure, but are in some measure enhanced by the removal of the one factor which might otherwise mask the true picture of the more important components. The author's mental concept of the mechanism of commutator-brush conduction apparently agrees with that of Mr. Hellmund, although no effort has been made to substantiate it by microscopic examination of the paraffin film. The only evidence that can be offered is the blackening of the wax film either by carbon particles from the brushes or by carbonization of the paraffin itself.

Messrs. Franklin and Linville have very capably pointed out the possible inaccuracies involved in making the separation of the total losses under load into known and stray-load losses whatever the method for determining them. Again the matter is one of definition, and final efficiencies should have correct values so long as the procedure is consistent. They also state that it is well established that the brush-friction loss is sometimes reduced by half between no-load and full-load. While this is quite conceivable, it would be helpful to a fuller appreciation of the part played by brush friction in the total losses to have further investigation of this factor presented in published form. The available information on this point is quite limited, and it may be that what is considered as common knowledge among manufacturers is as yet unreported in a form to make it available to independent investigators. The author here makes the plea that the manufacturers, whose designers are the ones to benefit most by the full discussion of this subject, themselves undertake and publish the results of careful and open-minded investigations. The investigation of the known as well as the stray-load losses would certainly aid in bringing the whole consideration of d-c machine efficiencies up-to-date and in line with the growing importance of the d-c machine.

The percentage values presented in the papers are not strictly in accordance with a general definition of stray load loss, in that they do not account for certain variations in "constant" losses which might work for the reduction of the total stray load loss. These "known" losses were subtracted from measured total losses exactly as they occurred at the time of the test. The values are at least consistent with the original Test Code definition, and form a valid basis for comparing machines within a certain size class. The author himself would dislike to have these figures or any other figure so presented used as an argument in favor of the one per cent rule. Any agreement of the measured stray load loss with this one per cent figure must be taken as accidental, as the only satisfactory means of arriving at stray load loss is to measure it.

It has been proposed from time to time that a measurement of stray-load loss might be had by determining the increase in power needed to drive the rotor of a machine when it is short-circuited and sufficient excitation applied to circulate full-load current in the armature. Curve *E* of figure 3 of the paper shows the trend as the excitation is reduced, with a stray load loss 50 per cent greater at 28 per cent excitation than at normal excitation. Subsequent tests of the same machine by this short-circuit method show a loss of 300 watts, or practically double that for normal operating conditions. The conclusion is inescapable that this method has no place in the array of possible methods for determining stray-load loss.

This discussion does bring out the need for a more complete treatment of stray-load loss in the Proposed Test Code, so as to make the definitions general and correct, and also to specify rather definitely what procedures are to be followed in determining stray-load loss by measurement.

The discussion offered by Mr. Miller is very much appreciated, as it amplifies some points given only brief mention in the paper. The wide variability in performance of the commutator is easily demonstrated by almost any operation that is performed upon it, or by any conditions to which it is subjected. The continual fluctuation of armature current under no-load conditions is indicative of this variation, and sanding of the commutator produces notable and long-lasting increases in loss, with accompanying heating effects. Likewise, paraffining produces a marked decrease in loss, and it was observed in some instances that the total rotational loss was decreased by as much as 20 per cent. This represents a considerable decrease in actual power for any machine, and the cooler operation of the commutator at no-load was very apparent. The paper by Doctor Glass, which was not available at the time of writing the paper, is a very fine treatment of the subject and is worthy of considerable study.

As to the terminal-to-terminal drop, it was not stated just how this was obtained, and the conclusion that it was measured while stationary is not surprising. However, the armature was actually rotated slowly by hand so as to procure average sliding contact conditions. It has been the author's experience that this represents the running contact conditions with sufficient accuracy that it is far preferable to measuring the contact drop at full speed. Although this is not in accordance with code provisions, the intent was to measure the drops as they actually occurred at the time of the test, so as to measure the actual stray-load loss.

The series winding was left out for purposes of the comparative tests for loss with different methods where the armature current conditions could not possibly be duplicated, but the commutating winding was included at all times. This established the magnetization as being entirely from an independent source and not dependent on the variable armature currents. That the ampere-turns of shunt and series fields are not of equal effect in producing flux is open to little question. It may be possible that, once the validity of the test method has been established, the series winding should be left in so as to give its full effect as under operating conditions. It is interesting to note that this will require reversing the series coil on the machine which serves as the generator of load-back couplet.

The experience with regard to hysteresis effect when changing armature current is well included at this point. It was mentioned briefly in the paper that this same effect was present in the machines tested, particularly when the low excitation run was made. It is felt that the effect is of minor importance at normal saturations of the machine, but is well worth keeping in mind as it explains some manipulative difficulties that are otherwise surprising. As to shaft currents, no attempt was made to determine the presence of shaft currents, or in general to separate out the relatively smaller components of the stray-load loss. The size of the machines tested seems wholly unrelated to the amount of the loss measured, and it is the author's feeling that even on small machines, where efficiency guarantees are of any importance at all, some tests must be made to measure the actual value of that loss.

A detail of test procedure has been questioned by Professors Schilling and Koopman, and it is sufficient to say that both first and last readings of no-load loss were taken in accordance with standard procedure, the duplication being made to be certain of no major change in rotational loss during the test. Any difference of minor order was either prorated according to the time elapsed, or taken as an average of the two readings.

The author is very glad to have the discussion from Mr. Hughes, of Brighton, England. He raises a question on a point which is often forgotten in the consideration of stray-load loss; namely, the original source of what is included in this rather comprehensive term. Certainly a sizeable portion of the stray-load loss is due to a change in the total iron loss of the machine with the increase in load current. It does not seem possible, however, to relate the stray iron loss to flux conditions when it is practically impossible to separate the loss into the many components which of necessity are included in it. The test suggested by Mr. Hughes is one which would appear to have some promise for getting at the iron loss component, provided the machine in which one is interested has a compensating winding. The analytical expression for total iron loss should be helpful in considering the problem from this rather fresh point of view.

Too often the original source of the approximate methods of dealing with anything become so obscure that the very obscurity tends to strengthen the belief that those methods are exact, and it remains for one from afar to break down the time-honored acceptance. It is this desire, academic though it may be, to bring a fresh consideration of the stray-load loss to the d-c machine which prompted the author to undertake this work originally, and it is his hope that further progress can be made until the accurate treatment of the d-c machine is as well established as that for any other, particularly in view of the present major trend to d-c machines for large mill drives where certain inherent characteristics make them indispensable.

Unsymmetrical Short Circuits on Water-Wheel Generators Under Capacitive Loading

Discussion and author's closure of a paper by C. F. Wagner published on pages 1385–95 of volume 56, 1937, AIEE TRANSACTIONS (November 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 27, 1938.

C. Concordia (General Electric Company, Schenectady, N. Y.): There are two points which should be brought out in connection with this paper. First, because of the test method, i. e., the application of the capacitor or reactor load at the moment of short circuit, the transients are different from those associated with an actual fault on a system in which the capacitance or other load is continuously in the circuit. Also, due to generator regulation, even the steady state overvoltages observed are not the same as those obtained with similar permanent loads, the apparent overvoltages being high for capacitance load and low for inductance load. Near the point of third-harmonic resonance this difference may be about 30 per cent, but can of course easily be corrected by calculation. In spite of these differences, the test overvoltages are undoubtedly qualitatively the same as those which would have been obtained in tests simulating more exactly the condition of an actual fault.

Second, it should be emphasized that the ratio x_q''/x''_d, upon which the overvoltages due to line-to-line faults largely depend, is not simply dependent upon whether or not the amortisseur end rings are connected between poles, as might be inferred from the paper. In the machine used in Mr. Wagner's tests, an unconnected damper winding gave a relatively large ratio, but as the machine size, in particular the relative axial length, is increased the difference between unconnected and connected damper windings becomes smaller. Thus, for large low-speed water-wheel generators, unconnected damper windings may be much more effective than would be indicated by tests on a small machine. Moreover, the amortisseur design may have considerable effect on the ratio x_q''/x_d'' aside from the connection between poles. Finally, the many other functions [see "Overvoltages Caused by Unbalanced Short Circuits" (Effect of Amortisseur Windings), by Edith Clarke, C. N. Weygandt, C. Concordia] of amortisseur windings should be considered in every application.

Because of these factors, the electrical performance characteristics of an amortisseur can be more accurately described in terms of the ratio x_q''/x_d'' than in terms of whether it is connected or unconnected between poles.

W. V. Lyon (Massachusetts Institute of Technology, Cambridge): This comprehensive analysis of Mr. Wagner's is particularly interesting to me. In 1926 Rene Brosens working under my direction obtained oscillograms of the open-phase potential when a line-to-line short circuit occurs on a three-phase generator delivering a condensive load. As a generator he used a wound-rotor induction motor having a leakage coefficient of 0.046, and consequently the ratio x_q/x_d' was about 20. For this reason Brosens obtained a much higher open-circuit potential than Mr. Wagner. Brosens noted a peak potential of about 18 times normal peak line-to-line potential. By applying the simplified theory proposed by Boucherot in 1911 which neglects resistance and is consequently similar to the "constant flux linkage" theory of Doherty, Brosens checked the peak values of potential within about 10 or 15 per cent. He made no analysis of wave form. A brief report of Brosen's work was sent to a few operating companies calling their attention to the possible danger of overpotentials with these conditions of operation. Apparently at that time the results were considered of only theoretical importance, and so far as I know no attention was paid to the warning.

Fundamentally the excessive steady-state potential on the open phase is due to the difference in the transient reactances in the two axes. Even with a salient-pole machine it is theoretically possible to have a damper winding for which these reactances are equal.

C. F. Wagner: Mr. Concordia is quite right in his point that the transients resulting by suddenly applying a short circuit across two terminals and a capacitor across the sound phase simultaneously will give a transient different than if the machine had been loaded before the application of the short circuit. I had made tests (see figure 11) with the capacitor connected before this short circuit and had come to the conclusion, however, that the difference is rather small. The general question of the effect of load regulation is discussed to some extent in my paper. It likewise will make a difference. As a matter of fact it is possible to enumerate a host of factors that make a greater difference (and a much greater difference) than the factors of whether this capacitor had been connected before the fault or whether the regulation had been included properly. In practice it rarely occurs that the ideal conditions of an unloaded line to which a short circuit is applied are satisfied. Usually the machine under consideration is feeding power over a line to the end of which other synchronous machines are connected. These machines will usually have a damper winding or its equivalent. Upon the inception of an unbalanced fault, abnormally high voltages may be produced but if the breaker at the receiving end of the line opens first, then a condition is satisfied under which much higher voltages may be produced. But in the transition to this, the important condition, note that an intermediate circuit condition was passed through. The transients during the beginning of this final circuit condition would in all probability be entirely different than if a similar unbalanced fault was applied to the unloaded machine, for example, while it is connected to the capacitance of the line.

Mr. Concordia also infers that many of these conditions can be calculated easily. It must be remembered that the resonance conditions are the important points. But for this condition the armature resistance is very important in determining the maximum voltage. A method of analysis which will predict the maximum voltages must be capable of introducing the effect of resistance. Further, in the absence of a knowledge of these resistances it is impossible to predict the maximum voltages. As shown in my paper the resistance varies with the frequency and while these data were obtained for a machine without damper windings a similar relation should apply for machines with damper windings. In this case the current distribution between bars and within the bars will vary and affect the resistance. A quantitative analysis should therefore include this factor quantitatively and must apply for the resonance points. A comparison of figures 13 (*b*) and (*c*) of my paper gives some idea of the effect of armature resistance near a resonance point.

With regard to Mr. Concordia's second point that the inference might be taken from my paper that the effect of damper windings is simply dependent upon whether the damper winding is connected or not connected, I wish to call his attention to my statement near the end of my discussion of this subject (page 1391) which reads: "In any case figures 8*d* and 8*h* show that dangerously high voltages can be attained with this kind of damper unless precautions are taken to insure that the ratio x_q''/x_d'' is made more nearly equal to unity." With nonconnected windings much can be done by properly locating the end bars to reduce this ratio considerably.

But after all most of these points are more of academic than of practical importance. The analysis of this subject either by the method presented by Clarke, Weygandt, and Concordia or by the method presented by myself indicates that the general factors affecting the problem are pretty well understood. The practical solution appears to be to install non-connected damper windings with as low values of x_q''/x_d'' as is practical to obtain.

Professor Lyon's discussion is very interesting. It is unfortunate that Brosens did not extend his analysis at the time to salient-pole machines. It is quite probable that his theories in this case would have received a more favorable reception.

Stray-Load Losses of D-C Machines

Discussion and authors' closure of a paper by E. W. Schilling and R. W. Koopman published on pages 1487–91 of volume 56, 1937, AIEE TRANSACTIONS (December 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 27, 1938.

R. F. Franklin and **T. M. Linville:** For discussion, see page 401.

T. H. Morgan: For discussion, see page 403.

R. E. Hellmund: For discussion, see page 404.

Victor Siegfried (Worcester Polytechnic Institute, Worcester, Mass.): This paper is a valuable contribution in that it gives further proof of the need for a renewed consideration of the matter of stray load loss in d-c machines. The fact that a test method for determining these losses is available in which confidence can be placed is demonstrated by the results that Schilling and Koopman present. The writer is in whole-hearted agreement with their conclusion that the loss must be measured rather than assumed to have some arbitrary percentage value.

The authors do not state the ratings of the machines used, nor whether series or commutating windings were in use during the tests. This information would be helpful in interpreting their results. Assuming, however, that the machines are rated at 110 volts, and taking rated current as 16.85 amperes, it would appear that rated full-load input is 1,854 watts. Reading from curve *B* of figure 10, a value for stray load loss of 35.5 watts per machine, the loss is thus 1.91 per cent of full load input. Such a figure shows that the loss is one which cannot be neglected even for small machines, and that the one per cent rule of the Standards is wholly inadequate to take account of this loss.

Schilling and Koopman are to be congratulated on the consistency of points on the curves presented in the paper. This shows careful work in the conduct of the tests, and further demonstrates that stray-load loss is actually measurable. Too long has the feeling been expressed that stray-load loss is not measurable. Their paper does present one method for determining it with results checked by an independent method, as shown in their figure 7. The experience of this writer is much the same—that stray-load loss can be measured, that consistent results are obtainable, and that independent methods give practically identical results.

E. W. Schilling and **R. W. Koopman:** In his discussion Professor Siegfried raises the questions of rating, and connection of the series and commutating-pole windings. The machines were rated two horsepower, and the commutating-pole windings were connected in the usual manner. The series fields, however, were not used.

The writers are greatly pleased by the interest in this paper shown by engineers of the larger manufacturing companies. Messrs. Hellmund, Franklin, and Linville point out that brush friction changes between no load and full load. In order to measure bearing and brush friction at conditions as near to actual load conditions as possible the machines were run until constant temperatures were reached before loss measurements were made, and friction loss was measured at no load immediately thereafter. Thus brush friction was measured at very nearly the same temperature, commutator surface conditions, and humidity as prevailed under load. As to the question of reduction in brush friction due to increase in current which is raised by Messrs. Franklin and Linville we have no data; however, it is evident that the change was not great enough to cause the low values of load-loss to swing negative. The writers admit that it is hard to determine accurately the brush-drop loss; however, the values obtained at rated current checked closely the conventional two volts. At any rate, by making allowance for increase in brush drop with increase in current, more accurate data for stray-load-loss were obtained than would have been obtained had the conventional value been used.

If armature I^2R loss had been calculated at the conventional temperature of 75 degrees centigrade and brush drop taken as two volts, some of the lower values for stray-load-loss would have certainly been negative. This would have been logical procedure had one definition of load loss been adopted; however, the writers attempted to adhere to the definition for stray losses given in the table under paragraph 2.105 of American Standards for Rotating Electrical Machinery, *C*50.

The writers do not feel that they have presented adequate data to question the magnitude of the present percentage taken for stray-load loss, but they do believe that they have presented sufficient evidence to show that the use of a constant factor for all conditions of speed and field is quite inadequate.

Switching Surges With Transformer Load-Ratio Control Contactors

Discussion of a paper by L. F. Blume and L. V. Bewley published on pages 1464–75 of volume 56, 1937, AIEE TRANSACTIONS (December 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 27, 1938.

R. C. Van Sickle (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The data presented in this paper are of interest to those concerned with switching surges in general, as mentioned by the authors, so a few remarks on their relation to other available circuit-breaker data are pertinent. It is particularly necessary to point out that although the phenomena in high-voltage circuit breakers are similar to that presented here, the magnitudes are much different and in particular the voltage surges are much smaller.

The load-ratio control switches were tested on power sources of 1,000 volts, 20 amperes alternating current and 125 volts, 25 amperes direct current. The speed of opening was relatively fast and currents of 15 amperes were unstable and extinguished without waiting for the normal current zero. The overvoltages produced by them were enormous. By the interruption of direct currents, overvoltages of 67 times normal were encountered and of alternating currents overvoltages of 18 times normal. Such voltages on high-voltage lines would be disastrous so it is fortunate that certain limiting influences exist.

The maximum dielectric strength between contacts of a high-voltage breaker is relatively less than that of contactors. Moreover the increase in the gap between contacts during the period of current zero is also relatively smaller. Consequently, if the arc is interrupted before a normal current zero, by one of the usual forms of high-voltage circuit breakers, the maximum voltage which can be produced is limited by the dielectric strength of the arc path to a magnitude which does not damage other apparatus. A paper "Breaker Performance Studies by Cathode Ray Oscillograms" presented before the Institute in 1935[1] contains an illustration, figure 4, which shows an excellent example of this voltage phenomena which occurred during the interruption of 20-kv, six amperes by a high-voltage breaker. The arc was unstable and restruck about 30 times before a current zero. However, the contacts had not separated sufficiently to enable the breaker to withstand the recovery voltage at this current zero so the arc restruck and continued as an unstable restriking arc until the next current zero. During this time the current flowed through the breaker as a series of impulses with a time interval between them less than 0.0001 second. On the magnetic oscillogram it looks like a normal half-cycle of current during an arcing period. Even with this extremely unstable arc, the maximum overvoltage produced by the circuit breaker was about ten per cent of the normal crest value of voltage.

The effect of having a relatively higher dielectric strength is shown in figure 6 of the same paper. It is a cathode-ray oscillogram of the interruption of a 70-kv 20-ampere circuit by an experimental 287-kv high-speed breaker. In this case, the arc is unstable for approximately two-thirds of a cycle but due to asymmetry of the current two normal current zeros occur in this period and the arc restrikes after the first one. The rapid speed of operation and high dielectric strength of the breaker produce overvoltages approximately 3.5 times the normal peak of the 70 kv applied. However, a pole of a 287-kv breaker must open 87 per cent of 287 kv which is a voltage having a crest value equal to the overvoltages obtained on this test.

The paper by Attwood, Dow and Krausnick on "Reignition of Metallic A-C Arcs in Air" presented before the Institute in 1931[2] contains similar material and was based on arcs in low-voltage circuits. However, the overvoltages obtained were not as high as those given in this paper because the arcs were produced between stationary copper plates eight inches square and three-fourths inch apart. Some of these arcs became unstable and extinguished before the normal current zero. However, the arc terminals were not being separated rapidly and consequently the maximum voltages produced by the current rupture were limited to about the normal crest voltage either by a glow discharge or by a complete dielectric breakdown between electrodes. On the basis of the oscillograms in these papers it is reasonably safe to conclude that unstable arcs in high-voltage circuit breakers do not produce as great overvoltages as are shown in the paper under discussion and that they probably are limited to considerably less than twice the normal voltage crest.

The maximum value of the current at which the arc becomes unstable is given as five amperes for the a-c tests. This is higher than the 0.6 amperes for the arcs between stationary copper plates where conditions were less favorable for arc extinction. However, in the 70-kv 20-ampere circuit previously referred to, where conditions were more favorable for arc extinction, the arc was unstable through the small loop of an asymmetrical wave during which the magnetic oscillogram indicated a smooth loop with a crest value of 19.2 amperes.

The interruption of a 44-kv 330-ampere short circuit with the current becoming unstable at 11 amperes is shown in a paper, "Arc Extinction Phenomena in High Voltage Circuit Breakers" presented before the Institute in 1933, figure 6.[3] These data indicate that the current at which the arc can suddenly extinguish is a function of the effectiveness of the deionizing activity and the rate of current decrease.

The maximum value of direct current at which the arc extinguished abruptly is given as 15 amperes on page 1464 and as 20 amperes on page 1470.

The reported erratic recovery of dielectric strength may be due in part to the interpretation of the data. It was assumed, as given in the conclusion, that "Restriking was so abrupt as to be practically instantaneous and was followed by an immediate dielectric recovery." The discharge of a current through the arc space during a restrike requires the ionization of the arc path and, although the dielectric strength of the path does not fall to zero, it must be appreciably reduced. The magnitude of the ionization is indicated by the oscillograms which show that these restrikes pass the equivalent of a steady current of several amperes. Consequently, the assumption that the envelope of the restriking voltage is the curve of dielectric recovery against time and that it gives the dielectric strength at any instant is not justified. The first figure referred to in this discussion illustrates this point also. The recovery voltage builds up to about 25 per cent of the normal voltage crest following the relatively long deionizing period at the first current zero. (At the left of the oscillogram.) After the restrike, the value of voltage at which the arc restrikes is only about eight per cent of the normal voltage crest. The ionization produced by the restrike has definitely reduced the dielectric strength.

The curve of the recovery of dielectric strength as a function of time should be a broken curve with an abrupt drop at each restrike and with the following rise indicating the recovery. However, due to the various factors controlling the deionization, the recovery will still be erratic but not in the manner indicated in this paper.

REFERENCES

1. ELECTRICAL ENGINEERING, volume 54, 1935, pages 178–84.
2. AIEE TRANSACTIONS, volume 50, 1931, number 3, pages 864–8.
3. AIEE TRANSACTIONS, volume 52, 1933, pages 850–60.

D. C. Prince (General Electric Company, Philadelphia, Pa.): The investigations and data obtained by these authors disclose some very interesting phenomena applicable to currents and voltages of the order of magnitude of load ratio control, the field in which they have worked. In endeavoring to extend the reasoning to other fields, particularly the circuit-breaker field, a certain amount of caution must be observed. Arc phenomena of the nature of those which they are investigating in general are very different if the scale is changed. It is therefore not in general safe to assume that overvoltages would be multiplied by the same amount if different current values were used, or that they would be multiplied by the same amount if different voltage values were used.

For both higher currents and voltages, circuit-breaker experience over a considerable period of years shows that overvoltages, where they occur, are of relatively small magnitude. In the range covered by the authors however these phenomena are very interesting and have counterparts in other fields such as mercury-arc-rectifier arc backs, etc.

R. D. Evans and **A. C. Monteith** (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): It is significant that three of the papers presented at this session deal with switching transients. This is indicative of an increasing interest in the problem not only from the theoretical point of view but particularly from the practical standpoint because of problems actually encountered in the operation of power systems. It should, however, be clearly recognized that the paper by Messrs. Blume and Bewley deals with a very special type of transient problem. These remarks are not to be construed as a criticism of the paper because the authors have indicated this fact in the title and have stated it in the early part of their paper.

Concerning the authors' investigation, we would like to comment on certain specific points. In reviewing the paper we find no mention of the characteristics of the source, a factor which we believe to be of importance. If the abrupt forcing of current zero takes place there will be an oscillation on the source side as well as on the load side of the circuit-interrupting device and the voltage appearing across the device will be the vector sum of the oscillating voltages appearing on both sides.

The authors have divided the recovery voltage problem into three parts: first, the normal-frequency component; second, the high-frequency component dependent on the capacitor voltage; and, third, the high-frequency component depending on the reactor current. Our paper "The Determination of Recovery Voltage by Analytical and A-C Calculating Board Methods," presented at the

1937 summer convention, dealt with this case and the results for interruption at other than current zero were discussed in connection with figure 25 of that paper. In considering these factors it is believed that the third is only of importance in dealing with relatively low current values, such as discussed by the authors. In a normal power circuit with typical values of fault current, it is believed the third factor becomes less significant, especially on the higher-voltage circuits.

The authors have inferred the same "dielectric-recovery curve" whether there is or is not restriking. The shape of the dielectric-recovery curve will be materially modified when restriking takes place and the shape will be dependent upon the number of restrikes. In high-voltage circuit breakers it will depend on the contact separation. Therefore, the phenomenon is not as simple as indicated in figures 6, 7, and 8.

Production of high-frequency transients on a large scale is not to be expected on power systems with conventional types of current interrupters from the factor of the forcing of the current zero as described by Blume and Bewley. Instead, it is our opinion that such voltage, if encountered, will be due to the successive re-establishment of the arc path at such intervals as to produce cumulative oscillations. In this connection it should be pointed out that the process of producing cumulative oscillations requires certain rather definite relations between the system recovery-voltage time curves and the insulation recovery-time curves to make it possible. If the shapes of these curves differ from that which is required, the oscillations do not become cumulative and the voltages will be limited to about the value corresponding to a simple arc suppression or to that of one restrike. It is because of this difficulty in setting up the essential conditions for cumulative oscillations that has made their probability so small that they are rarely encountered.

Summarizing, it is our opinion that if high voltages due to switching transients on main power circuits are to be encountered they will take place principally through the mechanism of restriking just described. Furthermore, the mechanism of producing overvoltages by the sudden forcing of current zero appears to be a factor of small importance on high-voltage apparatus and circuits but of increasing importance as the voltage is reduced until it becomes a major factor in the special type of problems to which the authors have limited their investigation.

J. D. Cobine (Harvard Graduate School of Engineering, Cambridge, Mass.): The authors are to be commended for their instructive presentation of the nature of the voltage appearing across an impedance when its current is interrupted by a switch.

The curves of figures 6 and 7 assume that the duration of current subsequent to a restrike is zero and there is no change in the dielectric recovery curve, while the oscillograms of figures 9, 10, and 11 show that the voltage falls at approximately a uniform rate for a measurable interval of time during which current is apparently flowing. Now if an arc current flows after restrike the dielectric strength of the gap has obviously been reduced to a low value and an entirely new dielectric recovery curve must be plotted starting from the time the new current flow is interrupted. Thus in figures 6 and 7 a new dielectric recovery curve must be drawn for each restrike. These dielectric recovery curves will be different from the first because of two important factors, namely, the current of the new arc will have changed and the length of the gap at the time of its interruption is different. The new arc current will be less than the old and therefore the dielectric recovery will increase at a more rapid rate than before. Lengthening of the gap will also raise the recovery voltage curve. Of course, if the restrike current is very small and of short duration there will be little change in dielectric recovery. It would be of great value if the authors could give some values of current that are typical of the restrikes presented.

The shapes of the experimental curves of dielectric recovery, figure 11, are quite interesting, but somewhat obscure as to details. What is the difference between the several curves for the same shunt capacitance? Was the initially interrupted current the same in each case? If so, what was its value?

It may be that the erratic behavior of the restriking voltage of the switch is due to the presence on the contacts of impurities having low work-functions. These impurities would also be vaporized into the arc column and by their low ionization potentials lower the reignition potential. Some research of the writer (Electrical Engineering, volume 53, 1934, page 1081) has brought out the marked effect of impurities in lowering the reignition voltage of a short arc. Small amounts of these impurities were found to produce random variations in the reignition voltage. It is obviousely very difficult to have a commercial device free of impurities so that the switch was probably thoroughly contaminated.

Protection Features for the Joint Use of Wood Poles

Discussion and authors' closure of a paper by J. O'R. Coleman and A. H. Schirmer published on pages 131–40 of this volume (March section) and presented for oral discussion at the power transmission session of the winter convention, New York, N. Y., January 27, 1938.

Sidney Withington (New York, New Haven and Hartford Railroad Company, New Haven, Conn.): This paper indicates the great advantage of broad-minded co-operation between power companies and communication interests, permitting the solution on a purely rational and engineering basis of problems which may be of somewhat controversial nature. Both classes of utilities, the electrical engineering profession, and the public generally are to be congratulated on such co-operation.

The public utilities commission of the State of Connecticut, 1922, stimulated among the utilities in the state the compilation of rules and specifications governing joint wood-pole-line construction carrying power circuits of more than 5,000 volts, and communication circuits. These rules provided for construction on a basis mutually agreeable to all interests concerned and saved both power companies and communication companies a very considerable amount of money in duplicate construction, which would have been necessary if each class of public-service companies had been obliged to construct its pole lines independently of the other. That was one of the earliest instances of such joint action among the utilities interested, and was a notable example of successful co-operative effort in the solution on a rational basis, of problems which might otherwise have continued to be troublesome and expensive to all concerned. It is indeed a source of gratification that such co-operation is being continued.

H. A. Dambly (Philadelphia Electric Company, Philadelphia, Pa.): This paper marks an important advance in the co-ordination of electric power and telephone systems. It was early recognized that for two services which so generally supply the same customers, design based on keeping the two systems widely separated was not practical in the long run, and that any solution which did not permit both systems to occupy the same general area and the same streets and highways was unsound from the long point of view. Joint use as compared to separate lines for many situations is a further step in the recognition of this principle. Further, the advantages of joint use which have been conclusively demonstrated over many years in the lower voltage field clearly indicated the necessity for developing means to permit similar operation at the higher voltages. This paper presents a much needed answer to these situations.

The paper is particularly timely in view of the rapidly increasing demands for electric service which in turn have brought many companies face to face with the problem of raising primary distribution voltages in order to meet these demands. Many of these systems are now operating on a joint use basis at 5,000 volts or less, and the necessary pole plant investment to accommodate both systems has been made. Under these conditions the need for suitable design features which will permit continuance of satisfactory joint operation at the higher voltages is evident.

By co-operative arrangement between the operating companies involved and the joint subcommittee on development and research of the Edison Electric Institute and the Bell System, the protective features outlined in this paper have already been worked out for a number of specific situations throughout the country, and it is believed that reasonable solutions can be reached in any specific situation.

In discussing separate lines versus joint lines, the statement is made that in rural and thinly settled areas it has been generally practicable and desirable to construct separate lines. It is recognized that types of construction widely different from normal span lengths may affect economies. However, it seems to me that in these areas one of the principal advantages of joint use, namely, the saving in avoided investment in poles with consequent saving in annual charges may be obtainable, particularly if planning is done on a broad forward-looking basis. Economies are needed to minimize the cost of both services to these rural customers. While the application of the protective measures in these areas involves somewhat different problems than in suburban and urban areas, the methods outlined in the paper should be applicable in these rural areas.

A. H. Schirmer: No one will question Mr. Dambly's statement that every reasonable economy should be practiced to minimize the cost of power and telephone service to rural customers. However, experience to date in studying specific situations, particularly those involving the long-span type of construction which has recently been used by most power companies in rural areas, indicates that, in general, there is no economy in joint use of lines in such areas, even from the structural standpoint alone. In other words, rural telephone lines on separate poles can, in general, be maintained at an annual charge less than the yearly cost of placing such circuits on jointly used poles. Furthermore, the inductive co-ordination problem in rural areas is frequently a difficult one even where separate power and telephone lines are used, and this difficulty may be definitely increased where both the power and telephone circuits are on common poles.

Lightning Strength of Wood in Power Transmission Structures

Discussion and authors' closure of a paper by Philip Sporn and J. T. Lusignan, Jr., presented at the power transmission session of the winter convention, New York, N. Y., January 27, 1938, and published on pages 91–101 of this volume (February section).

F. E. Andrews (Public Service Company of Northern Illinois, Chicago, Ill.): It is desired to emphasize conclusion 8 in the paper to the effect that the data presented add greatly to the knowledge of the impulse insulating property of wood in transmission structures. This paper appears to provide a basis very much more satisfactory than any information heretofore available on the design of wood-pole transmission and line structures to withstand impulse voltages.

This discussion is presented from the point of view of operating experience of 33-kv wood-pole transmission lines, using pin-type insulators without ground wire, with nine feet of wood between phases and the equivalent in insulating value from line to ground of 800 to 1,000 kv minimum on the basis of information in the paper (from figure 12). This operating experience indicates very greatly improved operation, that is, reduction in line tripouts, with this construction in comparison with conventional construction, that is, construction using steel crossarm braces and without impulse insulation in the guys.

Many cases have been noted where lightning has discharged over a structure without power follow or line interruption, the location of such cases being indicated by splinters on the poles or crossarms. In the cases where power follow has caused tripouts this has usually been found to be due to an arc between phases and in a number of instances, as indicated by burns on the conductor, this has taken place through air in the span away from the pole with minimum phase to phase distance of 7.3 feet. This experience indicates that there is no practical spacing with 33-kv single-pole construction at which power follow will not occasionally occur, although the wide spacing appears to materially decrease the susceptibility to power follow by comparison with results obtained with conventional construction.

In order to have a complete answer to the problem of lightning interruptions to lines of this type so that performance can be definitely estimated or predicted, it seems necessary to obtain in addition to lightning flashover data of the character covered by this paper, data on factors influencing power follow. It is believed that data showing the effect of the variables which govern the tendency for power to follow and maintain an arc after lightning flashover are quite necessary if best use is to be made of the lightning strength data in the present paper.

The use of the data on impulse strength of wood and porcelain to provide maximum resistance to lightning flashover within the dimensional limits of practical construction when combined with information on expectancy of power follow when lightning flashover does occur, should greatly increase the practical value of the data given us in this paper. It is to be hoped that the authors will continue their work to cover the problem of power follow.

P. B. Stewart (Cincinnati Gas & Electric Company, Cincinnati, Ohio): We have reviewed this article with a great deal of interest. We note in particular the reference to the reduced insulating properties due to moisture retained in wood poles.

Several years ago we made a study of the electrical resistance of wood poles. This work was covered in an article prepared for the American Wood Preservers' Association and can be found in their proceedings for the year 1936. In this study we found that the conductivity of wood varied with the moisture content. In most cases creosoted pine poles had lower resistance than cedar poles. This, however, was due to lack of proper seasoning.

It may be that there is a definite relation between the electrical resistance of wood and the impulse insulation strength of wood. This relation might hold true either above or below the fiber saturation point of the wood. In our study we found that a variation of moisture content above the fiber saturation point of wood had little effect on the electrical resistance. After the material had been seasoned below the fiber saturation point, a small variation in the moisture content had considerable effect on the electrical resistance.

Wood is a product of nature and has many variations. For this reason it is very difficult to determine accurate values from laboratory studies unless a very large number of tests are made. It is also very difficult to assimilate natural rain conditions due to the slow absorbing qualities of wood.

This article will be of great value in the design of wood-pole transmission lines.

L. G. Smith (Consolidated Gas Electric Light and Power Company of Baltimore, Md.): A paper of this nature is quite valuable to those designing transmission and distribution lines, since wood is of considerable benefit as insulation in raising the impulse flashover values. The formulation of these data so that they may be used as design information is of particular importance. It is frequently desirable to calculate the impulse level of new designs of lines in advance of their installation as otherwise wood insulation may be used wastefully and balanced designs not obtained. Moreover it is undesirable to have to test each design contemplated. The data given by the authors make design calculations of impulse levels possible. The ideal design is one in which a balanced design is obtained, that is, one in which the impulse flashovers from phase to phase and phase to ground on all phases are approximately equal.

Several years ago tests were made by the Locke Insulator Corporation for the Consolidated Gas Electric Light and Power Company to check certain designs of 13.2-kv, 35-, and 115-kv lines. As a result of these tests balanced designs of lines were obtained. These

Table I. Summary of Impulse Tests on 13.2-Kv Wood-Pole Lines

Double-Circuit Upright Construction With Four-Kv Arm Four Feet Below Lower 13.2-Kv Arm Ground Assumed to Be on Four-Kv Neutral and Secondary Neutrals and on Guy Wire

Flashovers in Kilovolts With 1½ x 40 Microsecond Positive Wave

Voltage Impressed	No Guys — Steel Crossarm Braces	No Guys — Wood Crossarm Braces	Guys With Two Porcelain Insulators—Steel Crossarm Braces — Thirty-Degree Guy at Bottom Lower Brace Within Two In. of Four-Kv Neutral	Steel Crossarm Braces — Horizontal Guy — One Foot Below Lower Brace	Steel Crossarm Braces — Horizontal Guy — At Bottom of Lower Brace	Steel Crossarm Braces — Horizontal Guy — One Foot Below Lower Arm	Steel Crossarm Braces — Horizontal Guy — At Bottom of Lower Arm	Steel Crossarm Braces — Horizontal Guy — At Bottom of Upper Brace	Guys With Two Porcelain Insulators—Wood Crossarm Braces — Thirty-Degree Guy at Bottom Lower Brace Within Two In. of Four-Kv Neutral	Wood Crossarm Braces — Horizontal Guy — One Foot Below Lower Brace	Wood Crossarm Braces — Horizontal Guy — At Bottom of Lower Brace	Wood Crossarm Braces — Horizontal Guy — One Foot Below Lower Arm	Wood Crossarm Braces — Horizontal Guy — At Bottom of Lower Arm	Wood Crossarm Braces — Horizontal Guy — At Bottom of Upper Brace	Guys With Wood Insulators Wood Braces — Horizontal Guy — One Foot Below Lower Arm	Guys With Wood Insulators Wood Braces — Horizontal Guy — At Bottom of Lower Arm	Guys With Wood Insulators Wood Braces — Horizontal Guy — At Bottom of Upper Brace	No Guys — Exp. Pro Gaps Multiplex Conn. Steel Braces	No Guys — Pole Grd. Wire Steel Braces
Column No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
A phase to ground	765	840	555	705	655	495	395	345	900	685	600	*495	*395	335	*840		*840	108	555 610 (−)
B phase to ground	920	1,230 1,020 (−)	675	895	*675	795	700 750 (−)	530	1,020	1,190	985	875	725	505	*1,230 *1,020 (−)	*1,230 *1,020 (−)	*1,230 *1,020 (−)	83 91.5	410
C phase to ground	530 445 (−)	710 690 (−)	345	465	*345	445	360	345	600	720	590	485 530 (−)	*360	335	*710 *690 (−)	*710 *690 (−)	*710 *690 (−)	94	345
A phase to C phase	705	*705		*705					*705	*705	*705				490	420	415	89.5	*705
B phase to A phase	700	*700		*700		*700	*700		*700	*700	*700	*700	*700		*700	*700	*585	78.5	*700
B phase to C phase	655	*700	*655	*655	*655	*655	*655		*700	*700	*700	*700	*700		*700	*700	585	81	*655
C phase to C phase	335	*705								*705					*705			88.5	*335

(−) Negative impulse wave value. * Measurements were not made—values assumed to be unchanged from other conditions. Where no values are shown flashover will go to ground instead of between phases at minimum voltage. Horizontal guys brought out from center line of pole on same side as the phase wires under test.

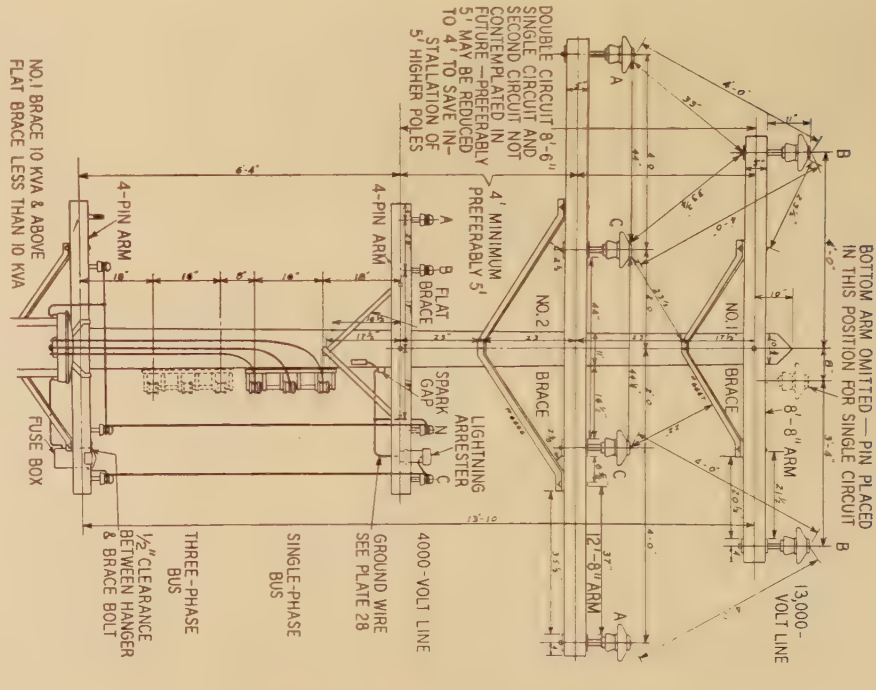

BOTTOM ARM OMITTED — PIN PLACED IN THIS POSITION FOR SINGLE CIRCUIT
B
B
4'-0"
8"
3'-4"
8'-8" ARM
13,000-VOLT LINE
NO.1
BRACE
4'-0"
A
C
C
A
12'-8" ARM
DOUBLE CIRCUIT 8'-6" SINGLE CIRCUIT AND SECOND CIRCUIT NOT CONTEMPLATED IN FUTURE —PREFERABLY 5' MAY BE REDUCED TO 4' TO SAVE INSTALLATION OF 5' HIGHER POLES
NO.2
BRACE
4' MINIMUM PREFERABLY 5'
LIGHTNING ARRESTER
A
B
FLAT BRACE
SPARK GAP
N
C
4000-VOLT LINE
4-PIN ARM
GROUND WIRE SEE PLATE 28
SINGLE-PHASE BUS
6'-4"
THREE-PHASE BUS
½" CLEARANCE BETWEEN HANGER & BRACE BOLT
4-PIN ARM
NO.1 BRACE 10 KVA & ABOVE FLAT BRACE LESS THAN 10 KVA
FUSE BOX

Figure 1

designs are covered in a discussion on page 199, AIEE Transactions, 1936. These tests were made on assembled structures. These test results were compared with the data contained in the authors' paper and were found to check very closely.

The results obtained for the types of construction used on 13.2 to 35 kv are shown in table I, for the type of construction illustrated in figure 1. Figure 1 also includes an alternate design for a single-circuit line, using the top crossarm only with a third insulator installed near the pole, which is shown dotted. The results of this type of single circuit construction are shown in table II. An alternative design is shown in figure 2, the results of test on this type of construction being shown in table III.

Table II. Summary of Impulse Tests on 13.2-Kv Single-Circuit Wood-Pole Construction

Ground Assumed to Be on Four-Kv Neutral on Four-Kv Arm, Seven and One-Half Feet Below

Flashovers in Kilovolts With 1½ x 40 Microsecond Positive Wave

Voltage Impressed	No Guys — Steel Crossarm Braces	No Guys — Wood Crossarm Braces	Angle Guys With Two Porcelain Insulators, Wood Braces — One and One-Half Feet Below Bottom of Brace Within Six In. of Four Kv	Angle Guys With Two Porcelain Insulators, Wood Braces — One Foot Below Bottom of Brace Within Six In. of Four Kv	Angle Guys With Two Porcelain Insulators, Wood Braces — At Bottom of Brace Within Six In. of Four Kv
B phase to ground			645	560	400
A phase to B phase	630	730			
B phase to C phase	570	575			

B phase is on the same side of pole as C phase.

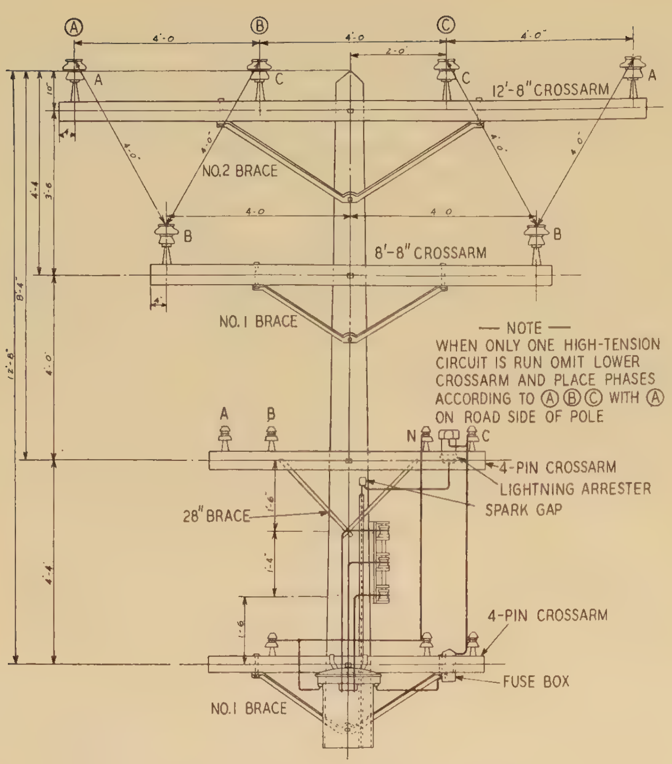


Figure 2 (left)

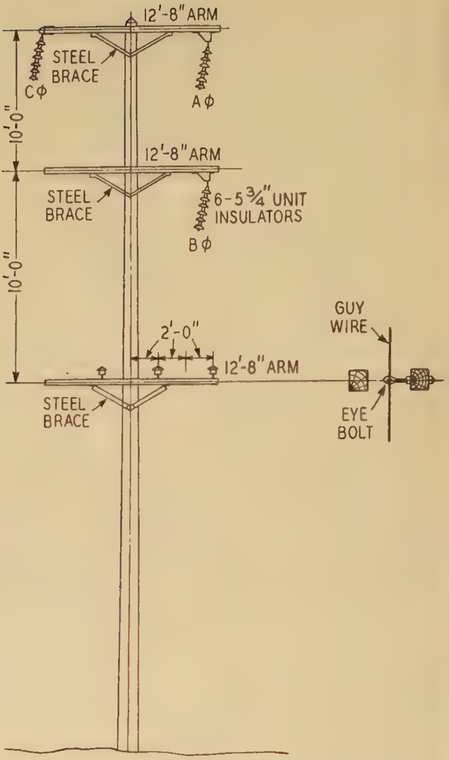


Figure 3 (right)

Tests were also made on a 66-kv type of structure, which was designed for future operation at 110 kv. This type of construction is illustrated in figure 3. The results of the tests on this construction are shown in table IV. Two types of arcing horns were used in these tests, the older type to which reference is made is the conventional type of horn, which had the effect of reducing the flashover of strings. In the new type of horn, the horn was straightened in order to effect the minimum reduction of flashover of the string.

In the tests on wood poles it is interesting to note the difference between the various types of poles. Our tests showed similar results in some cases, the moisture in the pole lowered the resistance sufficiently to permit the impulse generator to discharge through this resistance without obtaining an external flashover. One of the poles tested had an internal moisture content of from 112 per cent to 136 per cent. However, it is believed that if the generator had had sufficient current discharge capacity, external flashovers could have been obtained. Since pine poles immediately after creosote treatment may have a very high moisture content it is quite possible that the trouble noted by the authors may have been similar to that outlined above.

Another point of interest is the relatively small effect of the various sizes of insulators upon the flashover of the combination of pin-type insulators and wood crossarms, shown in figure 10 of the paper. It is believed that this is a very important consideration in the design of low-voltage lines. This feature may be utilized in the practical design of lines by choosing an insulator of sufficient size necessary to give the desired 60-cycle flashover and leakage characteristics. The remainder of the impulse level can then be obtained by the judicious use of wood, which usually will be at a lower cost than the cost for additional porcelain.

I. W. Gross (American Gas and Electric Service Corporation, New York, N. Y.): In the latter part of the paper the authors present impulse flashover data on typical transmission line structures carrying 33-kv and 66-kv circuits (figures 15 and 16). In figures 19*A* and *B* it is shown that the minimum impulse insulation of the line (which was phase to ground) was increased over 100 per cent for the 33-kv structure by the use of wood arm braces, wood bayonets supporting the ground wire, and an offset down lead.

While the gain in impulse strength is clearly apparent from the test results reported, it may be interesting to look at the operating record of this line before and after the above structural changes were made. The line which is 15 miles long is of standard two-circuit vertical configuration carrying a ground wire above the pole top. The ground wire is grounded every third pole, ground resistances ranging from 20 ohms to over 300 ohms. There are 483 structures in the line, 42 of them being guyed structures. The guys were insulated when the wood insulation was added.

During the four years prior to revamping, there was an average of 3.2 single-circuit outages per year due to lightning and 7.2 double-circuit outages per year. For the five-year period following revamping with wood insulation these were reduced to 2.2 and 0.6 on an average yearly basis. That is, the single-circuit outages were reduced 36 per cent and the double-circuit outages 92 per cent.

Where double-circuit lines are used to protect the continuity of service rather than for load requirements, the performance of the lines must be evaluated on the double-circuit outages alone, as a single-circuit interruption does not result in a service interruption. On this basis the improvement in performance of the above revamped 33-kv line is quite remarkable.

Table III. Summary of Impulse Tests on 13.2-Kv Double-Circuit Inverted Wood-Pole Construction

Ground Assumed to Be on Four-Kv Neutral on Four-Kv Arm Four Feet Below Lower Arm

	Flashovers in Kilovolts With $1\frac{1}{2}\times 40$ Microsecond Positive Wave					
	Angle Guy With Two Porcelain Insulators—Wood Crossarm Braces					
	At Bottom of Lower Brace Within Six In. of Four-Kv *C* Phase,	At Bottom of Lower Arm Within Six In. of Four-Kv *C* Phase		At Bottom of Upper Brace, Within Six In. of Four-Kv *C* Phase	One Foot Below Upper Arm Within Six In. of Four-Kv *C* Phase	
Voltage Impressed	$50\frac{1}{2}$ Degree Angle	50 Degree Angle	40 Degree Angle	40 Degree Angle	25 Degree Angle	14 Degree Angle
B phase to ground	730	605	655	550		575
C phase to ground				550	585	575
C phase to *B* phase			655			

Corresponding records are not at present available for the revamped 66-kv lines, as in some cases the reconstruction work was not carried out on complete lines, and in other cases sections of intervening steel-tower lines obscured the records. An over-all survey of the performance records of these lines, however, seems to indicate a reduction in outages comparable to the impulse-insulation improvement shown for these 66-kv structures in figures 20*A* and *B* of the paper.

R. L. McCoy (Locke Insulator Corporation, Baltimore, Md.): The paper by Messrs. Sporn and Lusignan is of extremely great interest. The authors are to be congratulated for having carried on a well organized and comprehensive investigation on this important subject. Significant light has been shed on many obscure factors which in the past have been given little or no study. This paper gives stimulation to further thought along this line.

In transmission structures we are interested in the over-all impulse insulation afforded by various combinations of wood and porcelain insulation. The data presented bring out in a striking way the fact that to obtain the most benefit from wood as an adjunct to porcelain consideration must be given to the proper co-ordination of these materials. Analyzing the data presented in the paper, that is in figures 10*A*, 12*A*, and 13, it is seen that the positive-polarity impulse strength of wood taken as an adjunct to porcelain insulators varies from approximately 130 kv per foot with pin-type insulators down to approximately 55 kv per foot with ten-unit strings of suspension insulators.

A variation of a somewhat similar nature is noticed in the negative-polarity impulse strength as an adjunct to porcelain in figures 10*B*, 12*B*, and 13. This suggests as the authors point out that particularly in the case of the longer strings of suspension units the stress distribution between the porcelain and wood elements is badly out of proportion to their respective impulse strengths. The authors suggest that this may be due to unfavorable relative electrostatic capacitances of the various elements.

In order to check this proposal a four-foot section of creosote-dipped well-seasoned crossarm having a cross section of four inches by four inches was tested in series with the following dielectric members:

(*a*) One-unit heavy-duty switch and bus insulator having a capacity of 53 micromicrofarads at 60 cycles.

(*b*) A two-unit string of standard five and three-quarter-inch by ten-inch suspension insulators having a capacity of 15 micromicrofarads at 60 cycles.

(*c*) A 13½-inch rod gap which should have relatively very low electrostatic capacity.

These dielectric members were selected because at standard humidity they have approximately equal full-wave impulse flashover values on a 1.5 x 40 positive impulse wave. All tests were made at an absolute humidity of 0.3 inch of mercury-vapor pressure. The four-foot wood section alone gave impulse strengths of 166 kv per foot positive and 154 kv per foot negative. The insulation added by this wood section to the switch and bus insulator, the two unit string of suspension units, and the 13 ½-inch rod gap were respectively positive polarity 153 kv per foot, 158 kv per foot, and 172 kv per foot, negative polarity 155 kv per foot, 148 kv per foot, and 167 kv per foot.

It should be noted that in these measurements practically the full impulse value of the wood itself was added while in the case of the rod gap the wood added more strength than it possessed by itself. This suggests three things, first, that perhaps the relative leakage resistance of the insulation elements is also important, or perhaps the relative surge impedances of the elements which would take into account not only the relative capacities but also the relative resistances. Second, that as the authors' data might be interpreted to suggest the impulse strength of the wood section should be large in comparison with the impulse strength of the insulator element. Third, that the distribution of stress between the porcelain and wood elements may be a function of their relative time lags.

It is a matter of observation that the time lag at the full wave flashover on pin-type insulators and short strings of suspension units,

Table IV. Summary of Impulse Tests on 66-Kv Wood-Pole Lines

Pumphrey to Annapolis Future 110-Kv Line Construction

Six Insulators per String—Pole Ground Wire

	Flashovers in Kilovolts With 1½ x 40 Microsecond Positive Wave															
	Guy Attached Six Feet Below Lower Arm										Guy Attached Four Feet Below Lower Arm at Various Angles to Pole				Six-Unit String Only, Straight Line Fittings	
	Old Type Arcing Horns				New Type Arcing Horns						New Type Arcing Horns					
	Straight Line Fittings	Angle Fittings			Straight Line Fittings			Angle Fittings			Straight Line Fittings, Insulators Vertical					
	Insulators Vertical	Insulators Vertical	30 Deg. Swing	45 Deg. Swing	Insulators Vertical	10 Deg. Swing	20 Deg. Swing	Insulators Vertical	10 Deg. Swing	20 Deg. Swing	17½ Deg. 65 In. Clearance	42½ Deg. 53¾ In. Clearance	51 Deg. 45 In. Clearance	60½ Deg. 36 In. Clearance	Old Type Arcing Horns	New Type Arcing Horns
Voltage Impressed Column No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A phase to ground	*750	725	680	540	*1,025	*940	*835	*995	*895	*770					*520	*580
B phase to ground	*750	755	680	560	1,025	940	835	995	895	770	1,010	810	685	560	*520	580
C phase to ground	750	725	800		*1,025										520	*580

Eight Insulators per String—Pole Ground Wire

	115-Kv Expulsion Protective Gaps, No Arcing Horns	115-Kv Expulsion Protective Gap in Ground Wire, Wood Guy Insulators Above and Below 13-Kv Arm	Guy With Wood Insulators Six Feet Below Lower Arm. Old Type Arcing Horns				New Type Arcing Horns					
			Straight Line Fittings Insulators Vertical	Angle Fittings			Straight Line Fittings			Angle Fittings		
				Insulators Vertical	30 Deg. Swing	45 Deg. Swing	Insulators Vertical	10 Deg. Swing	20 Deg. Swing	Insulators Vertical	10 Deg. Swing	20 Deg. Swing
Column No.	17	18	19	20	21	22	23	24	25	26	27	28
A phase to ground	470 490 (−)	905	*885	840		*490	*1,025	*930	*790	*995	*880	*720
B phase to ground	470 490 (−)	*905	*885	*840	585	490	*1,025	930	790	*995	880	720
C phase to ground	470 490 (−)	945 1,030 (−)	885				*1,025					

* Measurements were not made—values assumed to be unchanged from other conditions. (−) Negative impulse wave values. 13.2 kv on pole grounded in tests with old type arcing horns. No 13.2 kv on pole in tests with new type arcing horns.

say from one to five units, varies from four to eight microseconds, while on long strings of suspension units, ten units or more, it may run from 15 to 25 microseconds.

J. H. Hagenguth (General Electric Company, Pittsfield, Mass.): The authors have given the results of a very thorough investigation of the impulse characteristics of wood alone and wood in series with insulators.

Some tests on wood crossarms made in the high-voltage engineering laboratory in Pittsfield check the results obtained by the authors very closely. For instance, data published in a paper on "Impulse Voltage Strength of Insulators and Materials" by J. C. Dowell and C. M. Foust, figure 30 checks figure 4 of the paper for the flashover of pine at two microseconds almost exactly, while the Pittsfield values for the full-wave flashover are approximately eight per cent higher. Curves of figure 30 of the above reference begin to bend over considerably at about five feet—the flashover voltage of nine feet is only 36 per cent higher than at four and one-half feet—while the authors' figure 7, curve *A* indicates proportionality between flashover voltage and length of wood gap. In my opinion, it seems more reasonable to expect a smaller increase in flashover voltage for great length of wood, because the flashover of wood probably is a creepage phenomenon, which tends to be progressive, once an arc has started and the addition of a few feet of creepage path will not materially increase the flashover voltage.

Some investigation carried out on large-scale pole structures in the laboratory seem to check this contention. During these tests, wood crossarms with a length of as much as 11 feet and insulator strings of 9 to 15 units were in series. The ratio of measured to calculated (similar to table I of paper) flashover voltage was approximately 0.50, if the kilovolt values curve *A* of figure 7 of the paper are used, and 0.80 if the kilovolt values of the Dowell-Foust paper figure 30 for ten microseconds are used. The impulse insulation added per foot of crossarm during these tests varied between 30 and 50 kv per foot. The lower figure usually was associated with the longer wood gap. Lengths of wood poles up to 35 feet were arced over, when in series with an insulator string. During these tests it was also quite well established that the flashover voltage of an air gap 21 feet above ground was approximately the same as the same gap spacing with standard mounting. For instance, a 90.5-inch air gap 21.5 feet high, flashed over at 1,385 kv (1,400 kv standard rod gap) and a gap of 166 inches flashed over at 2,640 kv (2,530 kv standard rod gap). All these tests were made with 1.5x40 waves of positive polarity.

There appears to be some discrepancy between the results of figures 4, 5, and 7 of the paper. In figure 4, the flashover voltage of a pine crossarm of approximately 20 square inches is given as 530 kv at four feet, while figure 7 shows a flashover voltage of 610 kv for the same length. While this difference may be accounted for by the difference in treatment and general condition of the wood, these results do not seem to check figure 5*A*. The poles used for the test presumably had a larger cross section than the crossarm and should, therefore, be expected to have a relatively lower flashover voltage.

The authors mention very briefly the effect of rain on the insulation strength of wood, stating that a reduction of some 50 per cent might be obtained. Since the lightning disturbances usually occur under rain condition, it naturally would be of real importance to have more data taken under such conditions. It may, therefore, be of interest to compare dry flashover voltages as given in the paper with flashover voltages obtained under rain conditions in Pittsfield with a precipitation of 0.2 inch. The Pittsfield tests were made using a 66-kv pin-type insulator in series with wood crossarms.

Figure 4 (this discussion) shows a comparison between flashover voltages under the two conditions. It is a coincidence that the flashover voltages of the two insulators is the same, although one was tested, when dry, the other under rain. The considerable reduction due to rain in the insulation strength added by the wood is apparent especially for the first 12 inches. This is shown more clearly in figure 5 (this discussion) where the impulse insulation added to the pin insulator by an untreated pine crossarm is plotted, similar to figure 10*C* of the paper. Curve *C* on the figure 5 (this discussion) shows the ratio of wet to dry flashover, which is very low for short lengths of wood increasing to 50 or 60 per cent at about four feet, the maximum length investigated. This ratio is approximately the same for positive and negative polarity. For short lengths of wood, the calculations should, therefore, be based on the

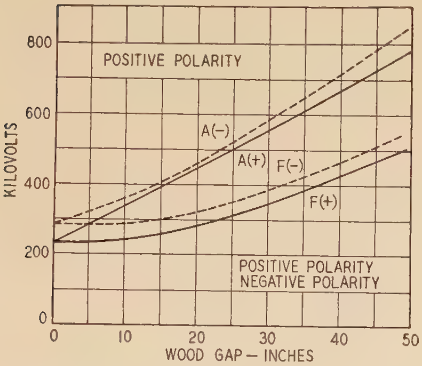


Figure 4. Impulse flashover characteristics of pin insulators plus crossarms—full-wave flashover

A—Creosoted fir crossarm, dry, same as curve *A*, figure 10*A* of the paper

F—New pine crossarm in series with 66-kv pin-type insulator rain test 0.2 inch per minute

Solid line—positive polarity

Dashed line—negative polarity

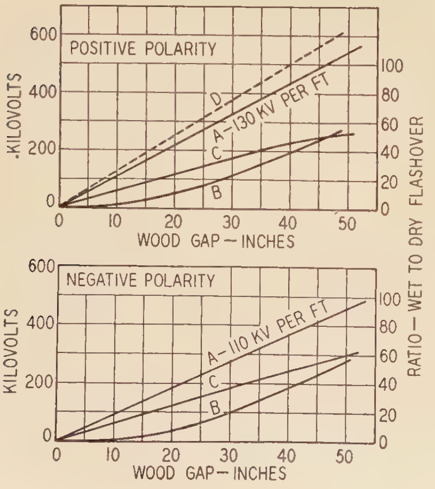


Figure 5 (left). Impulse insulation added to pin insulator by untreated pine crossarm—full-wave flashover

A—Curves for average insulation increase of 130 kv per foot and 110 kv per foot from figure 10C paper

B—Values obtained from wet flashover tests 66-kv pin-type insulator in series with pine crossarm, precipitation 0.2 inch per minute

C—Shows ratio of wet to dry flashover voltages

D—Pine crossarm alone

Figure 6 (right). Impulse flashover characteristics of pin insulators plus 36-inch wood crossarm. Positive polarity

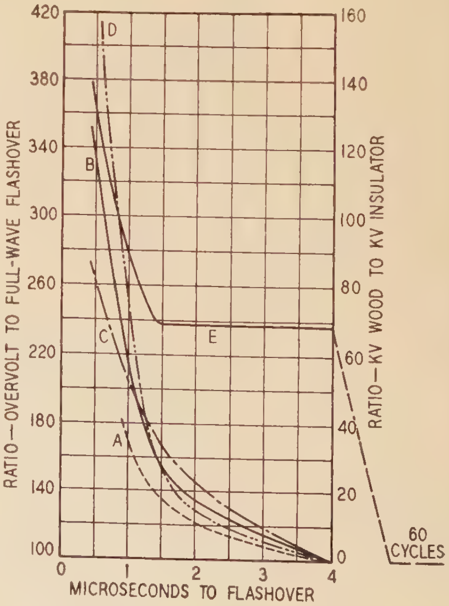
A—Fir crossarm, dry, same as figure 11*A* of the paper

B—New pine crossarm, rain test 0.2 inch per minute plus 66-kv insulator

C—66-kv pin-type insulator alone

D—Overvoltage of crossarm alone (when in series with insulator)

E—Increase in strength of wood at short times to flashover. Ratio of kilovolts across wood to kilovolts across insulator



wet flashover of the insulator only, for greater wood gaps the strength added by the wood probably will not greatly exceed a value of 50 per cent of those given in the paper. During these tests the overvoltages required to flashover at short times were measured for the insulator alone and for the insulator in series with wood and are shown on figure 6 for a 66-kv pin-type insulator with 36 inches of crossarm. Curve *D* of this figure represents the added strength of the wood in terms of overvoltage obtained by subtracting curve *C* from curve *B* and using the value obtained for the full-wave flashover as 100 per cent. Of considerable interest is curve *E* which shows the ratio between the flashover voltage of the insulator alone to the flashover voltage added by the wood at different times to flashover.

This ratio is almost constant down to 1.5 microseconds and then the insulation strength added by the wood becomes greater than that of the insulator. The other end of this curve indicates zero strength added for 60 cycles. Although the 60-cycle tests were made after the crossarm was subjected to a considerable number of impulses and was badly splintered, it might be expected that the 60-cycle flashover under rain of the added length of wood would be considerably decreased, since the pin of the insulator at this low frequency is practically at ground potential, when the wood is wet and flashover of the combination will occur at the flashover voltage of the insulator.

R. H. Earle (Line Material Company, South Milwaukee, Wis.): This paper is an interesting addition to our knowledge of the electrical properties of wood when used as an insulator on power lines.

This investigation, particularly when compared with former ones, shows rather a wide divergence of numerical test data. Such a range of test results is not at all surprising, however, in view of the other electrical properties of wood.

It is generally recognized that the resistance of wood shows enormous variations and depends not so much upon the species of the wood as upon the amount of moisture that it contains. This is not necessarily free visible moisture, but is rather the moisture which is absorbed by the cells of the wood from the atmosphere and the moisture content of the wood depends upon the humidity of the air to which the wood is exposed. Penetration of this moisture through the wood is rather slow. In ordinary outdoor weather conditions, such as wood structures encounter, the humidity is, of course, constantly changing with the result that the wood is practically always either absorbing or giving off moisture and since the moisture is transferred through the wood slowly, the actual moisture content represents a summary of the weather conditions for perhaps several months past.

It is accordingly seldom that the moisture content of a crossarm or pole will be uniformly distributed and since the electrical resistance of the wood depends so markedly on the amount of moisture that it contains, the pole or crossarm is electrically a bundle of resistors in series and parallel combinations and each resistor has a different value. The over-all resistance of the wood with nonuniform distribution of moisture is apt to be lower than would be the case if the moisture content were uniform throughout the volume of the specimen. Furthermore, in specimens of large cross sections there is likely to be a greater variation in electrical resistance across the section than is the case in pieces of smaller sections.

Applying these facts to some of the conclusions shown by the author's paper, we find a plausible explanation for several of the conclusions. For example, conclusion number 3 states that lower flashovers accompany larger wood sections. This would be expected since in general the resistance of the large sections is less uniform and lower than for the small sections.

In conclusion number 4, it is likely that fir and pine would show the same flashover if they had the same moisture content.

In conclusion number 5, it seems likely that the newly creosoted pine poles had not dried out to the extent that the old ones had, and conclusion number 5 also bears out the belief that impregnation only permits the pole to shed water a little more readily and aside from this does not influence the moisture content.

In conclusion number 6, it appears likely that the effect of the rain was twofold: first, to reduce the resistance of the wood by penetration of the fibers, and second, to form an electrolytic conducting path over the surface of the wood due to the rain dissolving impurities on the surface of the wood and thereby forming an electrolyte.

It appears that the extreme ranges of insulating values of wood crossarms, poles, and strain rods would be obtained by assuming the dry flashover of a corresponding length of air as the upper limit and by running further investigations on water-soaked timbers of some wood that soaks up moisture readily, such as beech, birch, or maple. Due to the comparative ease of impregnating these three woods with water, the results of electrical tests on such specimens would probably be lower than would be obtained in practice where the species would be more likely one of the firs, pines, or cedars.

Philip Sporn and J. T. Lusignan, Jr.: Mr. Andrews comments on the ability of wood to help prevent 60-cycle power current from following. This is an aspect of the wood insulation study which is well worth developing, but one which was not included in our program. There were so many factors affecting the impulse breakdown of wood, it was impossible for us to add tests involving 60-cycle follow current.

Mr. Stewart mentions some moisture studies he has made on wood poles and the variation in insulation value observed. We imagine that his work involves the 60-cycle phase of the problem, possibly with respect to pole burning or leakage. The manner in which he found moisture to affect insulation is interesting, but we feel that the behavior under impulse might be different from that encountered under power frequency. Our principal reason for this thought follows from the ability of moisture to serve as a conductor under the two conditions of 60-cycle and impulse surges. In other words, the moisture conduction must be electrolytic and involves movements of relatively slow electrolytic ions which would not respond to impulse voltages, lasting only a few microseconds, but which would serve as fair conductors of current for the longer power-frequency waves. We concur with Mr. Stewart in that a large number of tests are necessary in order to obtain dependable results on wood, chiefly due to the variable nature of that material.

The manner in which Mr. Smith has applied the results of laboratory studies to his line designs is most interesting. It is gratifying also that his results and conclusions concur so well with the authors'.

The tests which Mr. McCoy describes add very interesting information regarding the ability of wood to increase the insulation strength of a transmission structure. All of the reasons why wood does not add its full strength to the porcelain members are not clear to us as yet. We offered the suggestion that capacity distribution was an important factor, since under impulse, the conducting properties of moisture had little time to enter. However, we feel that the effect of the relative time lags of the porcelain and wood which Mr. McCoy mentions to be appreciable also. In fact it was a little easier at the time to explain the shape of some of our oscillograms by considering the possible time-lag curves of the porcelain and wood as well as what we consider to be the relative voltage distributions. The time-lag phenomenon which Mr. McCoy mentions wherein pin-type insulators and short suspension strings have shorter time lags than long strings is something which seems to hold with most long and short air breakdown paths over insulation. In other words, short rod-gap spacings and small switch insulators also have much flatter voltage-time curves than the longer gaps and insulators. We feel that this is probably due to electrode surfaces being relatively larger compared to the shorter air paths, thereby introducing most uniform electrostatic fields and approaching the flat time-lag characteristics of sphere gaps.

The information which Mr. Gross gives us regarding the greatly improved performance of his 33-kv line is very gratifying as it proves the value of laboratory tests in predicting the advantages, or disadvantages, of certain contemplated structure changes.

Mr. Earle goes into an analysis of the moisture factor in wood and its effect upon the electrical breakdown. We concur with his thoughts, although we want to emphasize that the distribution of the moisture has probably as much or more to do with the breakdown voltage as the total amount of moisture itself. In other words, we feel that the location of moisture areas both across the grain and along the axis are an appreciable factor in concentrating stress at certain points and thereby reducing the ultimate strength of the member as a unit. It is probably this factor that would make certain woods behave differently from others, even though they all have the same total moisture content.

Mr. Hageguth supplements our paper with some very interesting thoughts and laboratory data. He compares the results of the Dowell-Foust paper with our results and in some cases notes agreement. He questions the straight-line curves of our figure 7 which conflict with their figure 30 and suggests that wood flashover is a creepage phenomenon. Although only a few individual pole specimens were tested, an appreciable number of wood lengths were flashed over from one to ten feet so that we believe that our data of figure 7 are fairly reliable, in so far as the specimens tested are concerned. We feel that these specimens were rather dry and typical of those poles to be encountered in service so that the values from the curves could be used rather freely for estimating purposes. We question the existence of much creepage phenomenon, particularly in impulse flashover where, at the short times involved, there is little chance for much creepage. We note a statement at the bottom of the above figure 30 stating: "Whether the wood is dry or wet, soaked in salt water or creosoted, makes little difference." With this our results disagree considerably. The lower ratio Mr. Hagenguth obtains with our values obviously results because of the higher flashover values we measured for wood alone. His results showing no change in air gap above ground checks similar tests made by us after the paper was written.

The disagreement Mr. Hagenguth finds between the crossarm data of figures 4 and 5 and the pole data of figure 7 is something which we noted during the tests. In other words, the cross-section phenomenon of figure 5 applies only to crossarms. Equivalent section areas of poles gave higher breakdown values, particularly with fairly dry poles. We felt that this was due to the unbroken grain structures of the complete poles wherein the discharges were kept along the outside surfaces, whereas the crossarms were cut from inner whole sections and add no continuous outer shells.

The additional wet tests made by Mr. Hagenguth to supplement the few which we made are most worthwhile. The "coincidence" he mentions in regard to the equality of the wet and dry flashover of the insulator alone, we feel to be a reality. On wet impulse flashovers of porcelain insulators we have usually found the voltage values to be about the same as the dry values.

A New Correlation of Sphere-Gap Data

Discussion and author's closure of a paper by D. W. Ver Planck published on pages 45–9 of this volume (January section) and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 26, 1938.

P. H. McAuley (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): A simple and logical correlation of sphere gap sparkover data has been presented. It is particularly interesting to note that it brings out some of the discrepancies which we felt existed in the new AIEE values. The latter are averaged from tests made in different laboratories. Our values for the 50-centimeter sphere gap, for instance, are higher than the AIEE averages for the higher values of S/D. Table I, which includes some unpublished data, shows this condition. Similarly, our experimental curves show a value of 83 kv for positive-wave sparkover of the 6.25 centimeter gap at 3.125 centimeters spacing.

Table I. Average Sparkover Voltages for 50 Centimeter Spheres; Westinghouse Data Compared to AIEE Values

S/D	Westinghouse Positive	Westinghouse Negative	AIEE Positive	AIEE Negative
0.5	550	520	547	519
0.6	609	575	605	573
0.7	662	623	655	615
0.8	702	662	698	651
0.9	732	694	732	681
1.0	758	721	758	707

S = spacing; D = diameter.

The practice of averaging test data by empirical methods is well justified in the case of the sphere gap. The original data were obtained in several different laboratories. The gaps were made of different metals and no doubt had different surface conditions. Mounting arrangements varied considerably. Clearances were different even for separate tests on the same gap in one laboratory. Considerably more data were available on the 25- and 50-centimeter sphere gaps than on the other sizes. For these reasons, our data were correlated according to average gradient curves for given ratios of S/D. The present author has extended this process with gratifying results.

F. J. Vogel (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): The engineer responsible for the design of high-voltage apparatus has long used logarithmic paper for plotting experimental data and design information. This has been true for many years and may be found amongst the writings of engineers associated with several companies. A reference to this fact is given in the paper "Factors Influencing The Insulation Coordination Of Transformers, Part II" by P. L. Bellaschi and F. J. Vogel, Electrical Engineering, volume 53, June 1934, pages 870–6. This fact does not detract from Mr. Ver Planck's excellent paper since design engineers have not seen fit to call attention to the relationships existing between parts of similar shape.

In figure 1 of Mr. Ver Planck's paper, sphere-gap data are presented using ratios of spacing to sphere diameter as parameters. These data are plotted in figure 1 of this discussion, using given spacings as parameters. For a given spacing, it is seen that, as the sphere diameter is increased, the breakdown voltage becomes constant and presumably approaches that for plain surfaces. Values given in figure 1 of this discussion, for ratios of spacing of sphere diameter of 0.1, by changing the scale as shown, become breakdown values for plain surfaces. For comparison, points taken from Mr. Schumann's book on page 27 are shown. Schumann's values appear to vary as the 0.92 power of the spacing even down to very short distances. The use of the 0.88 power in figure 3 of Mr. Ver Planck's paper does not seem to be justified and perhaps points out an error in the sphere gap data for these distances.

Figure 2 of this discussion shows data established for design pur-

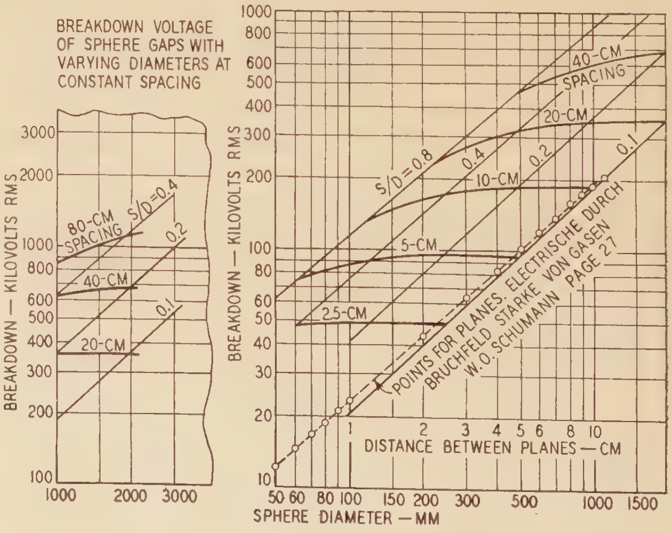


Figure 1

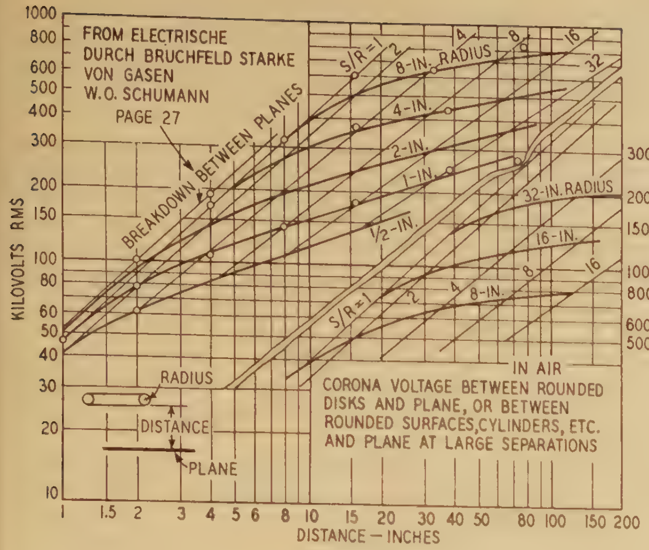


Figure 2

poses some years ago for the dielectric strength of rods and large-diameter parts. These data were obtained using sphere gap calibrations as standards of measurement but using spheres large enough to keep the ratio of spacing to sphere diameter one-half or less. The present calibration is not greatly different from the old one for these ratios, and the data are still sufficiently accurate for design purposes. It is to be noted that these data are plotted in the same manner as that used by Mr. Ver Planck. It is also of interest that these curves result in lower voltages than would be obtained by using the formulae derived by Mr. F. W. Peek, Jr., in his book "Dielectric Phenomena in High Voltage Engineering."

The use of curves, similar to figures 1 and 2, for design purposes, is desirable since they avoid calculation, give the design engineer a picture of the general relationships which exist, and permit the engineer to obtain his results quickly. When these two curves are used to help the engineer in forming judgment as to the clearances required for a given arrangement of parts, it is felt that figure 1 uses a better choice of co-ordinates, since the band showing the data is wider.

P. L. Bellaschi (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): Professor Ver Planck has presented an interesting paper on the sphere gap by plotting the new standard sphere-gap data on logarithmic graph paper and applying the principle of similarity for electrical discharges. It should be stated that the new standard sphere-gap calibrations have been well correlated in the first place, otherwise the good agreement in tables II and III would hardly have been expected.

In practice a number of factors affect the sparkover of the sphere gap and rules in its use are accordingly specified to minimize these effects within a permissible limit. In view of this, the agreement of the calculated values with the standard data is amply close to establish with assurance the various relationships indicated. Among these relationships the factor of relative air density and the probable corresponding corrections are worthy of attention.

Correlation of data naturally will bring to light major discrepancies. For example, in figure 3, the circled point near the 16-kv value, through which the dashed line is drawn, appears out of place. As a matter of fact, this is an extrapolated data point. In the final revision of the new sphere gap standards the few remaining extrapolated data points were subject to close scrutiny. As the result of tests in the various laboratories, the actual data value was established as being 17 kv, thus the dashed curve in figure 3 lines up quite well with the Schumann values.

The correlation of data in high-voltage technique and engineering is not only desirable but even essential. The author makes the statement that the similarity principle for electrical discharges seems not to have been fully appreciated by engineers in this country. This statement appears hardly warranted, for as a matter of fact, the relationship indicated in the paper for the sphere gaps as well as similar relationships for toroidal and cylindrical electrode arrangements have long been known to obey the principle of similarity for electrical design. These relationships have been put to useful application for a number of years by electrical engineers in the design of high-voltage apparatus.

D. W. Ver Planck: As pointed out by Mr. Bellaschi the consistently close agreement shown in tables II and III would have been unlikely if the data had not already been well correlated. In fact this independent check of the regularity of the data is evidence of the excellent work done by the subcommittee who prepared the new sphere gap calibrations.

Two of the three data which were found to be conspicuously out of line have since been revised in a subcommittee report dated December 1937, and they now conform to the new correlation. As a result, the circled point in the lower left-hand corner of figure 3 moves up to the solid line, and the last item in the 50 column of table III becomes 758 instead of 738. The single serious discrepancy remaining is the last item in the 6.25 column of table III, and if Mr. McAuley is right this value would become 83 instead of 81.8, which is within about 1.3 per cent of the calculated value.

Mr. McAuley's suggestion that the AIEE valves for 50-centimeter spheres may be a little too low is supported by the calculations for this size being consistently higher than the data. In fact if the data were revised in the direction indicated by Mr. McAuley, slight changes in the parameters K and α could be made which would result in an even closer agreement between calculations and data for all the other sphere sizes as well.

Mr. Vogel's figure 1 has for its theoretical basis the alternative functional form, equation 2, given in the paper, although generality has been lost by making the horizontal coordinate D instead of $D\delta$. The diagonal straight lines, which are for constant values of S/D, are described by the empirical formula

$$V = G(D\delta)^{\alpha}$$

where

$$G = K\left(\frac{S}{D}\right)^{\alpha}$$

and K and α have the same values given in the paper. These formulas and a table of numerical values for G were included in the paper as first submitted but for brevity were omitted before publication. While this form when plotted gives a greater separation of the lines for small values of S/D, it crowds them more when S/D is large.

Figure 2 indicates a relationship closely paralleling that in the paper and apparently known for several years but unfortunately withheld from publication until now. Here again, as in Mr. Vogel's figure 1 generality has been lost by not taking account of air density through the full use of the similarity principle. This figure would be enhanced in value if it were shown that the parameters of the straight lines for constant values of D/R conformed to an orderly relationship analogous to that given in figure 2 of the paper.

Mr. Vogel's figure 1 shows a considerable difference between Schumann's curve for a uniform field and the diagonal straight line for $S/D = 0.1$. Actually Schumann's data and the most recent revision of the AIEE data for $S/D < 0.2$ determine a single smooth curve. A reduction of Schumann's tabulated data to effective sine wave values gives points which lie from one to four per cent below those in the figure. If the discrepancy is not due entirely to an error in plotting it might be partly explained by a failure to take account of the fact that Schumann's data are for 20 degrees centigrade while those of the AIEE are for 25 degrees centigrade. Correction of Schumann's data to 25 degrees centigrade would shift the curve 1.7 per cent to the right since $\delta = 1.017$ for 20 degrees centigrade.

The use of the exponent 0.88 in equation 4 has been questioned. As stated in the paper the true curve for uniform field and small spacings is not linear when plotted to logarithmic scales, although the curvature is small. Figure 3 shows this curvature and that equation 4 gives a good fit for the range below $(S\delta) = 2.0$. For the range above $(S\delta) = 2.0$ and up to at least 20 the line determined by the parameters in table I for $S/D = 0.1$ is in close agreement with the data as can be seen in figure 3 and the first line of table II. The exponent 0.92 suggested by Mr. Vogel will be found to give good agreement in the intermediate range $0.8 < (S\delta) < 7.0$ if used with the coefficient 31.2.

Although it is much the best for the entire sphere-gap range above $(S\delta) = 2.0$, the power function type of formula, equation 3, is not as good for uniform field and small spacing as the formula

$$V = A\,(S\delta) + B\,(S\delta)^{1/2}$$

a type probably first used by Peek. The author has found that with $A = 24.4$ and $B = 6.8$ it agrees with Schumann's curve over the entire range $0.2 < (S\delta) < 9.0$ to within about 1.0 per cent.

A New A-C Network Analyzer

Discussion and authors' closure of a paper by H. P. Kuehni and R. G. Lorraine published on pages 67–73 of this volume (February section) and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 26, 1938.

W. W. Parker (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): 1. The paper which has just been presented is very timely because of the growing appreciation of the economies and advantages which accrue from the use of such facilities. As distribution systems become more and more complex the solution of their growing problems naturally becomes more difficult. Also the time required for analytical solutions increases beyond all reason unless improved methods are available. So it is that the members of the Institute should find this subject of live interest.

2. Several a-c calculating boards have been built for various companies for their private use and the investment made by these companies has been adequately justified from the excellent results which they have obtained. Along this line the *Electrical World* article of November 23, 1935, by Mr. T. G. LeClair, will probably be of interest. (Several slides were shown showing the a-c network calculator in Chicago, one in New York, one at East Pittsburgh and a new one just installed in Chattanooga, Tenn. This new one is shown in figure 1 of this discussion and employs a 100-volt one-ampere power level which is most convenient to use. This is the very latest in a-c calculating-board design.)

3. It seems that the best contribution that can be made to this discussion and one which will be of interest to the majority will be a brief outline of experience with one of these calculators. In the past eight years approximately 200 studies have been made embracing most of the systems in this country, as well as some from India, Mexico, and Canada. These can be roughly classified as follows:

50 per cent—Voltage-regulation and load-control studies to determine:

(*a*). The effect of new lines or synchronous condensers to improve voltage conditions.

(*b*). Transformer application both as to size and type, i.e., whether quadrature or in phase tap-changing equipment is desired.

(*c*). Choice of system voltage for new installations.

30 per cent—Stability studies both static and transient for determining:

(*a*). Power limits of lines or portions of network.
(*b*). Effect of increased machine inertia.
(*c*). Effect of high-speed excitation.
(*d*). Effect of high-speed fault clearing.
(*e*). Effect of circuit layout.
(*f*). Effect of auxiliary equipment such as reactors, neutral resistors, etc.
(*g*). Effect of connections of "topping turbines" to system.
(*h*). Effect of high-speed reclosing.

In fact, it is very doubtful if the many applications of 30-cycle reclosures on 110-kv systems would have been made if it had not been for the possibility of adequately predetermining just what would happen with an alternating current network calculator.

15 per cent—Short-circuit studies for determining:

(*a*). Breaker application.
(*b*). Relay application.

5 per cent—Miscellaneous studies including secondary-distribution-network studies, theoretical and special design problems.

4. The above classification does not include the voltage-recovery studies which are covered in a paper presented at this convention by Messrs. Evans and Monteith, entitled "Recovery Voltage Characteristics of Typical Transmission Systems and Relation to Protector-Tube Application."

5. These studies have resulted in system economies by obtaining (1) the most effective use of existing facilities, (2) the deferring of capital expenditures, and (3) the determination of the type and location of new equipment.

6. Summarizing, the use of the a-c calculating board or network calculator is being more and more appreciated by planning engineers, system operators, utility managements and even, at least in one instance by a public utility commission.

R. C. R. Schulze (Public Service Electric and Gas Company, Newark, N. J.): There are several points which have not been mentioned yet in the discussion. The principal one I have in mind is the ease of operation of this new G.E. analyzer. There are several features

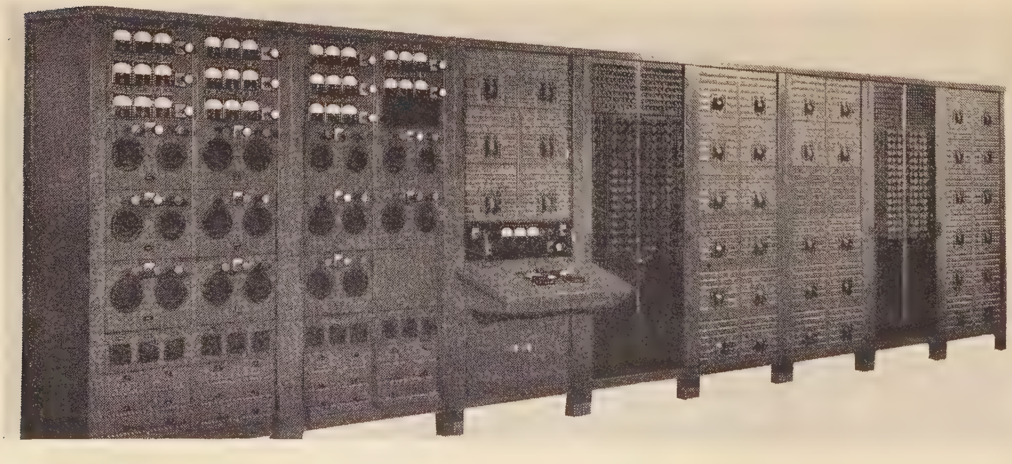


Figure 1

that make operation easier. One is the fact that loads can be set up as resistance and inductive reactance in parallel—so that watts and vars can be adjusted separately. Anyone who has tried to adjust a load with resistance and reactance in series will appreciate the convenience of the parallel connection.

Another factor is the arrangement of jacks and plugs. By making all connections in one (or two) places, the time involved in setting up a network is reduced, it is easier to see just what has been set up, and there is less chance of an error in the connections. We have had ten years of very satisfactory experience on our d-c table with this method of making connections.

The metering scheme is quite flexible, and permits reading almost anything desired. The ability to read watts and vars directly saves a large amount of slide-rule work. This not only saves a large amount of time in the analysis of the data, but it also saves time when adjusting the loads and generator units when making an analyzer setup.

Aside from the technical features of the master meters, the use of light-beam instruments is a distinct help to the analyzer operator. There is a reduction in eye-strain, since it is unnecessary to lean over a meter and squint at the pointer and its reflection with one eye. With the light-beam instrument the reading is essentially the same from any angle, so both eyes can be used. Also, it is possible to read these meters from anywhere in the room, not to the last tenth of a division, of course—but with a fair degree of accuracy. This means that one man can both adjust a load impedance and read the meter from that position, so that it is possible for one man to set up and adjust a network. Of course a second and even a third man would be useful, but the point is that this analyzer can be operated conveniently by one man.

I might add that our experience agrees with that mentioned by several of the previous discussers, in that it is possible to obtain results on a calculating table in much less time and with better assurance of accuracy than can be done by slide rule. This has been demonstrated on several occasions.

Our experience with our d-c calculating table, and with the results obtained on several visits to an a-c calculating table, has been very satisfactory. This experience, plus the complexity of the problems in system layout and operation, has led our executives to purchase the first step of an a-c network analyzer of the type described here.

Mr. Kuehni mentioned the types of problems which are usually solved on the a-c analyzer. A telephone friend of mine inquired about the possibility of studying the inductive coupling between a telephone line and our power lines, and one of our engineers has already suggested the study of transients on our analyzer. It is evident that we are going to have a variety of problems offered for solution on the analyzer.

It is our belief that this analyzer will not only be of considerable help in solving our technical problems, but also the savings resulting from its use will soon pay its cost.

E. W. Kimbark (Polytechnic Institute of Brooklyn, Brooklyn, N. Y.): The network analyzer described in the paper is the third principal design which has appeared. The first one, located at Massachusetts Institute of Technology and built jointly by the Institute and the General Electric Company in 1929, operates on a frequency of 60 cycles per second with a base voltage of 200 and a base current of two amperes. The second design, of which several boards have been built by the Westinghouse Company, uses 440 cycles and a base of about 100 volts, one ampere. The new design uses 480 cycles, 50 volts, 0.05 ampere.

The decrease in base voltage and current of each successive design is closely related to advances in the instrument art. The MIT network analyzer originally used suspended-coil wattmeters and thermocouple ammeters and voltmeters, all of which were sluggish, particularly the thermal instruments. The Westinghouse analyzers introduced dynamometer ammeters and voltmeters, one coil of which was inserted in the network while the other was fed from an instrument phase shifter. By supplying the larger part of the instrument power from the phase shifter, faster instruments were obtained without increasing the burden on the network. In the new analyzer described in the paper a great reduction in instrument burden without sacrifice of speed or accuracy has been effected by the development of suitable amplifiers.

I have had the opportunity of operating both the MIT network analyzer and the new General Electric analyzer and can testify to the improved "usability" (as the authors term it) of the new design. The elimination of calibration tables and plugging diagrams, the centrally located switches eliminating the need for an operator to move the instrument plugs, the fast easily read light-beam instruments, the fact that all three instruments indicate simultaneously, the good voltage regulation of the generator units and their independent continuous phase and magnitude adjustments, all contribute to this usability. Messrs. Kuehni, Lorraine, Thompson, and Slinger are to be congratulated on their excellent design of this new network analyzer.

A frequency in the neighborhood of 500 cycles per second has been chosen by two different groups of network analyzer designers and therefore seems to be well established. This frequency permits the use of smaller reactors and capacitors than those required at 60 cycles with the same voltage and current base. The use of a much higher frequency would increase the difficulty of limiting undesired electromagnetic and electrostatic coupling between network elements to a negligible value.

For experimental work the use of 60 cycles and of the higher voltage and current base has proven very desirable at MIT, as it permits various transformers, rotating machines, and instruments which are not part of the regular equipment of the network analyzer to be pressed into service.

A fair number of studies made on network analyzers have been concerned with transformers for controlling power flow in a loop by means of phase shift, and, although the required results have always been obtained from the analyzers, there has been no really satisfactory and convenient means of representing on the analyzer the phase-shifting transformers of the power system.

A very interesting and ingenious form of network analyzer (described in British patent specification No. 476,164) has been invented by Charles L. Blackburn, and put into service for the firm of Merz and McLellan in London. In the Blackburn network calculator an impedance unit (representing resistance and reactance) consists of two three-winding transformers with ratios controlled by tap switches and serving to connect magnetically four electrically independent circuits, the voltages of which represent respectively in-phase voltage, quadrature voltage, in-phase current, and quadrature current of the represented network. Such an impedance unit is furnished with four six-pole sockets, and the various units are interconnected by six-conductor flexible cords and plugs. This seems very complicated compared with the conventional form of network analyzer. However, the Blackburn calculator affords a ready representation of the following, all of which are obtained with difficulty on the conventional analyzers: (1) negative resistance, (2) transformer of complex ratio one to a for representing simultaneous faults, etc., (3) transformer with phase-angle control.

A large portion of the studies made on network analyzers are concerned with transient stability. In these studies generator swing curves are obtained step-by-step. The network analyzers have facilitated what was formerly the most laborious part of the process, the determination of the outputs of the several synchronous machines for given angular positions of their rotors. The other parts of the process, especially the computation of the changes of angular position of the generators in a small time interval, although relatively simple, are now the "bottle neck" of the procedure, keeping as many as four to six men occupied in contrast to one man operating the network analyzer itself. I venture the prediction that in the future generator swing curves will be drawn automatically on an output table, one pencil for each generator. This will be accomplished by an interconnection of a network analyzer and a differential analyzer, two integrators of the latter being used to solve the equation of motion of each generator. The electrical output of each generator unit will control through a watt relay and servo-mechanism the displacement of the first integrator. The output of the second integrator will rotate the phase-angle dial of the generator unit and also actuate a pencil. Such an arrangement would greatly speed up a stability study. One necessary feature of this arrangement, a generator unit having good voltage regulation, has already been developed by the authors of the paper.

H. L. Hazen (Massachusetts Institute of Technology, Cambridge): As a preliminary comment I wish to say that the paper by Messrs. Kuehni and Lorraine describes a fine piece of engineering equipment that has resulted from excellent engineering design. It should aid materially in developing the growing appreciation on the part of power-system engineers of the great power of an a-c network analyzer for the study of power-system operation. When these engineers have once experienced the facility with which they can study the operation of their system in miniature, they usually become enthusiastic about this method of study.

In this discussion I wish to review the development of such a-c network analyzers by stating in broad terms the nature of the essential design limitations in such devices, and to sketch briefly their development as determined by these limitations.

After the development of the technique of power-system representation by static apparatus (reference 6 of the paper) had been made, the design of a device which would be effectively applicable to actual commercial problems was found to be restricted by two primary limitations. The first and most important is that imposed by instrumentation. The second, less fundamental but a rather troublesome detail for the designer, is imposed by the difficulty of proportioning the units—particularly the inductive-reactance units—to properly represent their prototypes.

The effect of the instrument limitation is clearly shown by a consideration of the three principal designs of network analyzers to date; namely, the jointly designed and constructed MIT-General Electric Company analyzer erected at MIT, the Westinghouse design, and the General Electric design reported in the present paper.

In the analyzer at MIT the design with the metering originally provided was developed around the minimum burden for which a-c instruments of good accuracy could be built at the time of its development. These burdens were of the order of 1.5 to three milliamperes for potential elements, and roughly 0.1 volt for current elements. The criterion was adopted that an instrument potential element should not impose a burden, in comparison with a five per cent system load, of more than one or two per cent, and that an instrument current element similarly should not increase the impedance of a series element having a five per cent drop by more than about one per cent. This indicated current and voltage bases for the device of about two amperes and 200 volts, respectively. Assuming the analyzer to be in operation with ten generating stations each capable of 300 per cent of base output, the power requirement for the board is in excess of 12 kva, single phase, which evidently requires a sizable main supply generator in order to maintain reasonable voltage balance on the primary side of the phase-shifting transformers representing the generators. This indicated the use of 60 cycles because of the cost of substituting a higher-frequency generator for the 75-kva, 60-cycle, sine-wave generator already available in the laboratory. The limits of error set for this first design were one per cent for all units and somewhat lower limits for most of the instruments. These tolerances have been found, in the light of subsequent experience, to be unduly severe—a fact which has enabled the subsequent designs to be made somewhat more convenient in operation. The original metering equipment in this design was rather show—a condition that, as mentioned below, has been entirely corrected with recent modernization of the metering equipment of this original analyzer.

While this MIT-General Electric design was in progress the Westinghouse Company started on a somewhat different attack. They reduced the instrument burden by using dynamometer-type instruments and exciting one winding from an independent source that could furnish any desirable amount of power. This resulted in a sufficiently low burden for the other coil of the dynamometer instrument to permit its direct insertion in a network whose nominal current and voltage are somewhat less than those of the first-mentioned design. These instruments have a fast response. Two such instruments were used—one as a voltmeter with a low current requirement, and one as an ammeter with a low potential drop. This design uses a frequency of 440 cycles, which reduces the weight of the reactor units which are necessary to obtain appropriate reactance-to-resistance ratios, and also makes practicable reactor units with decade steps. This design of board has proved very useful. With the separately excited type of instrument the accuracy of readings is directly dependent upon the accuracy of setting of this excitation, both in magnitude and phase, and careful operation is therefore required to get good results. Nevertheless the effectiveness of this design is indicated by the fact that a number of such boards are in successful operation.

In the third design—that described in the paper under discussion—a quite different instrument technique has been used which has resulted in a very marked reduction in the current base. Specifically, the use of precision linear amplifiers in connection with semi-standard instrument elements has permitted the reduction of the voltage and current bases to the 50 volts and 50 milliamperes mentioned in the paper. This use of small base quantities, together with the use of 480 cycles, has resulted in relatively light, small units, decade steps for inductance units, and fast direct-reading instruments. This design also has the additional advantage of a low base current; namely, that the resistance of the long leads required for central plugging can be tolerated. Thus it appears that this third design has succeeded in realizing most of the features sought in an alternating-current network analyzer. This new analyzer is about as simple to set up and operate as is possible in such a device, remembering that the problems to be studied are inherently complicated in the sense of involving huge quantities of detailed numerical data.

It may be mentioned, however, that this new development—significant as it is—has not rendered earlier devices obsolete. The new metering techniques are just as applicable to a board such as the 60-cycle analyzer at MIT. In fact new, fast, direct-reading instruments have been incorporated into this analyzer which are described in a paper in preparation for publication. The new instruments, including a semi-standard portable wattmeter using a linear, degenerative feedback amplifier in the potential circuit, have been demonstrated to be sufficiently fast so that the speed at which readings can be made on this analyzer is determined not by the time which is required for the instruments to furnish indications, but by the rate at which the data can be reliably recorded. Thus the rate at which results are obtained is substantially the rate at which an engineer can record the readings obtained. This older analyzer requires somewhat more man power (estimated at one assistant operator) because the low-impedance base of this device requires interconnecting the units, and plugging for the current measurements, at the units themselves rather than at a central point. Another way in which this older analyzer has required somewhat more time is in the use of calibration charts for the reactance units—a method adopted at the time of the construction of this analyzer when smaller tolerances were prescribed than have proved necessary for the usual system studies. Now a much faster and simpler scheme of determining reactor unit settings is used in which an extreme mis-setting of a unit may amount to about three per cent as against about one per cent for the more accurate procedure. This considerably reduces the total time required for setting up a system on this analyzer. With the new metering equipment which has been in continuous service for some months, and the shorter set-up time involved by using the less precise calibration, the unit at MIT can deliver results very rapidly and, in the hands of good operators, remarkably reliable data are secured in very reasonable lengths of time not greatly in excess of that required on the newer devices.

In the experience obtained over a period of years in the use of this analyzer, both by students of electrical engineering and by the engineers of commercial companies, it has been found that skilled operators add greatly to its effectiveness. This is particularly true in the case of the use of the board by commercial-company engineers who, although thoroughly familiar with the characteristics and peculiarities of their systems, often do not visualize the way that the system conditions in which they are interested can be most easily represented in miniature, or how the information they wish to secure from the analyzer can be most readily obtained. It has been found that the present complement of a skilled operator and an assistant, together with two company engineers—one to direct the study as a whole, and the other to record data—make a very effective crew. The directing engineer states what he wants, and the operator determines the manner of obtaining the desired results. With such a group it is found that work progresses easily and rapidly, and that the mistakes occasionally made are caught before an appreciable loss of time is involved.

Summarizing, I wish to say again that the new development described by Messrs. Kuehni and Lorraine represents the excellent result of first-class engineering design which marks a distinct step forward in the facilities available for studying power-system networks. At the same time, older equipment in which advantage has been taken of newer metering ideas is still very serviceable and competes with the newer equipment on fully equal terms as to accuracy, and on nearly equal terms as to time required.

L. A. Nettleton (Consolidated Edison Company of New York, Inc., New York, N. Y.): Mr. G. C. Crossman, of the Consolidated Edison Company, and I recently had the privilege of using the G.E. network analyzer in connection with some studies of the New York Consolidated Edison system. We found the network analyzer to be simple to set up and operate. The per cent basis for marking the line and load units and instrument scales proved to be convenient since our impedance values which had previously been established on a 100,000-kva base could be transferred directly to the analyzer units with no additional conversion, so that per cent watts and vars read directly as megawatts or megavolt-amperes.

In taking readings, the light beams swing across the instrument scales and become stationary almost instantaneously upon closing the circuit key. After turning the scale-selector switch to give the best scale reading, the voltage, current, and watts are read and the wattmeter switch thrown to read vars. One operator could read all four quantities on successive circuits as fast as they could be recorded. We expected some confusion to result from the large number of scale multipliers but in practice there was no trouble. The voltage multiplier was unity in practically every case and only the current multiplier, which applied also to watts and vars, was recorded with the readings.

The 100- or 150-scale division instruments can be read to about one-fifth of a scale division and the phase-angle dials can be set or read to about one-fifth of a degree. In comparing the readings of six or more circuits tied to a common point it was found that the total watts entering that point invariably checked to within one per cent of the total watts leaving the point.

The generator units proved to have very flat regulation, requiring only slight readjustment when loading conditions were altered. In short-circuit studies it was found convenient to throw the supply voltage switch to one-half or one-quarter normal voltage temporarily in order to check the short circuit current and insure that no circuits would be overloaded on normal voltage.

The instrument system worked perfectly during the two weeks of the study. There is no danger of overloading the ammeter since an off-scale deflection automatically short-circuits the ammeter shunt.

It is sometimes desirable to close two or more circuit keys at the same time to meter the combined circuits. However, it occasionally happens that two keys are inadvertently closed at the same time, joining together two circuits which may be at different potentials. Sometimes this causes a generator fuse to blow, resulting in a few minutes delay to locate and replace the blown fuse. As this condition may not be discovered immediately and as it is not always easy to determine visually whether or not a fuse is blown, it might be desirable to provide some means for indicating the presence of a blown fuse.

In our studies it was sometimes necessary to consider the effect of load-regulating transformers, controlling both voltage and phase angle on parallel feeders. The voltage control feature presents no difficulties since the analyzer is provided with auto transformers which can be connected in the circuit at the appropriate location and adjusted to the desired voltage ratio. However, where there is a difference in the desired phase angle on parallel feeders the problem is not so easy when the system is set up on a "one line" or single-phase basis. There are several methods of obtaining this difference in angle on one of the feeders, but all require considerable adjustment before a balance is obtained. In our case the required displacement was obtained by one generating unit in series with the circuit and the watts or vars supplied to or taken from the circuit by this unit were neutralized by another generating unit together with a series stabilizing reactance connected in shunt with the circuit. For each change in loading conditions these two generators were adjusted in voltage and phase angle until the desired displacement angle was obtained, and until the volts, watts, and vars read the same on each side of that point.

Since these methods require considerable juggling, it would be a great convenience in problems involving such load regulating equipment if devices were available that would introduce the desired phase angle in a circuit and maintain that phase angle difference regardless of voltage or loading.

G. C. Crossman (Consolidated Edison Company of New York, Inc., New York, N. Y.): The increasing size and flexibility of modern power systems has created problems which can no longer be solved quickly and easily by analytical or even d-c calculating-board methods but which require for such solution some sort of a-c calculating device, such as the network analyzer described by Mr. Lorraine and Mr. Kuehni. Continued system growth of many large power companies tends to increase the number of these problems to the point where it becomes desirable for these companies to own and operate such a calculating device themselves rather than rent existing ones. It would seem that the very small currents and high frequency employed in this network analyzer would present rather difficult maintenance problems to such a power company. While most of the testing and maintenance of the line, load, and generator units of the analyzer could probably be handled by the average test department, it would seem likely that the testing and adjustment of the amplifiers and master instruments would require rather special instruments and special training not ordinarily available in such test departments. It was not brought out in the paper whether the trimmer capacitors on the potential shunt are adjusted once and for all at the factory or whether they might require subsequent adjustment; such adjustments would seem to require rather sensitive and special instruments.

It would be interesting to know what instruments and general methods the authors have used or plan to use for the maintenance of their analyzer.

R. N. Slinger (General Electric Company, Schenectady, N. Y.): In their paper entitled "A New A-C Network Analyzer," Messrs. Kuehni and Lorraine have given an excellent description of this new device. As one of those who have had occasion to use the analyzer extensively since it was placed in operation, I have been impressed more and more as time goes on by the many ways in which the device can help engineers solve their problems and it would seem that a few remarks on this subject might be appropriate.

Any power company engineer who has been faced with the necessity of obtaining answers to any of the following problems, and particularly when on an emergency basis, will immediately recognize how helpful it would have been to him to have an analyzer available for his use. A list of some of these typical types of problems for which the network analyzer is especially adapted might include the following:

1. Effect of various amounts of synchronous condenser capacity on bus voltages at important stations under both normal and emergency operating conditions.
2. Determination of best location for new generation.
3. Determination of best arrangement of station or system connections for new generation in order to obtain the maximum degree of system stability and investigation of the effect on breaker interrupting duty.
4. Determination of the actual value of a proposed addition to a transmission or distribution system in terms of improved voltage conditions, increased stability limits, or reduction in the loading of existing circuits.
5. Determination of wattless flow around a system and selection of methods for reducing it to a minimum.

6. Determination of bank ratings in the case of a new transformer bank that is to be connected in a loop circuit or a network or the determination of the ratings of individual windings of a three winding unit for use in a loop circuit or network.

7. Determination of improvement in system voltage conditions to be expected from the addition of a voltage regulating transformer or a phase shifting transformer to a loop circuit or a network.

8. Determination of the time required for a synchronous generator to pull out of step after complete loss of excitation and the effect upon the rest of the system.

9. Investigation of the starting and pull-in characteristics of large synchronous motors connected to a transmission system at some distance from the nearest generating station.

10. Determination of relay currents under three-phase and unbalanced fault conditions, particularly on tie lines during transient disturbances.

All of these problems can be and are studied in part by tedious long-hand calculation methods, but the excessive amount of time and labor involved usually places a serious limitation upon the number of operating conditions that it is feasible to consider. When such problems are solved with the aid of an a-c network analyzer, it is possible to investigate many different operating conditions in a surprisingly short space of time. As a result, studies made in this manner can be and usually are much more comprehensive in nature, covering not only normal system connections and the variations that may be under consideration but also the emergency conditions which unfortunately seem to get overlooked in the average long-hand study until after these contingencies arise.

Perhaps it should also be pointed out that once a system network is set up on an analyzer, such as the one described by Messrs. Kuehni and Lorraine, it is possible to make several different types of studies on the system with practically no change required in the connections except to represent changes in the original conditions. Thus a power-flow study may be made on a system in order to determine circuit loadings, bus voltages, condenser capacity requirements, etc., followed by an investigation of breaker interrupting duties under short-circuit conditions. This may in turn be followed by an investigation of transient stability limits or breaker times required to maintain stability with certain specified power transfers. During the course of the stability study, tie-line currents may be read at troublesome relay locations with perhaps a more comprehensive short-circuit and relay study made immediately afterward. Thus the engineer responsible for system planning and design is able to obtain a much better appreciation than he could otherwise have, of the influence of existing and proposed stations and equipment upon system bus voltages, power flow, stability limits and breaker duty, and he can feel considerably more certain that he has not overlooked something of importance that should have been taken into account.

The analyzer which Messrs. Kuehni and Lorraine describe is particularly helpful in this respect since it enables the power system engineer using it to think in terms of system quantities with which he is already familiar, thereby enabling him to keep his thinking straight. This is made possible by calibrating the entire analyzer including the master instruments in per cent. Thus it is a simple matter to interpret the readings in terms of system quantities; for example, a reading of 65 per cent watts and 40 per cent vars would represent 65,000 kw and 40,000 reactive kva, respectively, on a 100,000-kva base or half those amounts on a 50,000-kva base.

This particular analyzer has been in operation only about six months but in that time it has been used for ten different studies by engineers representing 13 different power companies and industrial concerns. The studies have varied in length anywhere from one day to four consecutive weeks and have covered practically every one of the various types of problems previously listed. It is safe to say that these studies have not only solved specific problems but they have also done much toward giving a clearer picture of system performance to the respective groups than they have ever had before. Furthermore, the results of the studies in some instances were quite different than had been expected and occasionally brought to light new problems that had previously passed unnoticed.

H. P. Kuehni and **R. G. Lorraine:** The authors are highly pleased by the reception given this paper. The discussion has been of such constructive character as to add materially to its value. The growing importance of the analyzer as an engineering tool, particularly for utility engineers, has been stressed. It is gratifying to know that those who have used the analyzer described in the paper feel that it has the degree of accuracy and the speed, facility, and ease of operation that was expected.

Professor Hazen called attention to the importance of proper instrumentation in the design of an analyzer. It is interesting to learn that advances in measurement ideas were incorporated in the MIT network analyzer to greatly improve the speed of taking readings.

Mr. Parker has presented a comprehensive statistical analysis of the practical types of studies made with the analyzer. Of course, the individual studies are not, in general, quite as clean-cut as one might be led to believe from his per cent tabulation. In practice each study more nearly is a combination of several types, one usually leading to another as the occasion arises. Mr. Slinger described many of the ways in which the analyzer may be of help to the engineer.

Mr. Schulze has given an excellent discussion of the salient design features which contribute to the ease of operation of the new analyzer based upon his wide experience with network analyzers of different types.

There are undoubtedly network studies in which it would be desirable to have available special units to represent phase-shifting transformers as suggested by Messrs. Kimbark and Nettleton. However, these cases are quite rare at present. Because of the cost of such units, it was decided to use generator units for this purpose, even though they are admittedly somewhat more awkward to operate than phase shifting transformers might be. The integrators and servo-mechanisms used with generators for automatically recording swing curves, which Mr. Kimbark predicts will be integral parts of future analyzers, are at present in the same category with the phase-shifting transformers. These devices can be and may be incorporated in the analyzer when there is sufficient economic justification.

Mr. Crossman is of the opinion "that the testing and adjustment of amplifiers and master instruments would require rather special instruments and special training not ordinarily available in testing departments." It is the authors' belief that any one familiar with ordinary instrument calibration routine methods is perfectly qualified to check and adjust the instrument system by following a few instructions of very simple nature. With the exception of perhaps a small portable commercial cathode-ray oscillograph of a type which are so widely used today, no special instruments are required.

All adjustments of the instrument circuits, amplifiers, potential divider, and current shunts are made initially. Many months of experience has shown that with normal operation the adjustments and the calibration of the instrument system remain quite permanent over long periods of time. The parts which may require re-adjustments are designed to be easily accessible and are equipped, for example, with rheostats, trimmer capacitors, or test connection facilities.

In view of the stable performance of the instrument system, occasional simple routine check tests should suffice to indicate that the instrument system is in order. For this purpose a portable voltmeter calibrated at 480 cycles may be used together with the measured resistance part of a circuit unit to indicate that the light-beam voltmeter, ammeter, and wattmeter read correctly.

The potential divider and current shunt phase angles may be checked and if necessary adjusted with the aid of the analyzer master wattmeter, knowing that the power into an analyzer capacitor unit is negligibly small.

The amplifiers have simple rheostat and capacitor adjustments for matching the amplifier input and output in magnitude and phase angle. The cathode-ray oscillograph mentioned above, connected to a suitably located amplifier test jack, is merely used as a sensitive high-impedance null instrument to adjust the output-input voltage differential to zero.

In regard to maintenance of the rest of the analyzer circuits and units, it simply consists of checking and correcting with the analyzer master instruments any abnormal circuit performance. The conservative design of the elements comprising the circuit units and the low resistance contacts and connecting leads assures that the calibration of these elements remains very stable.

Transactions

Papers and Discussions Comprising Pages 423–92 of the 1938 Volume

Subharmonics in Circuits Containing Iron-Cored Reactors

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Synopsis: The performance of a series circuit consisting of a resistor, a capacitor, an iron-cored inductor, and a sinusoidal impressed voltage is specified by the non linear differential equation

$$\frac{d\psi}{dt} + ri + L\frac{di}{dt} + \frac{1}{C}\int i\,dt = E\sin(t+\theta)$$

in which ψ is an odd function of i. Particular solutions of this equation, showing the effect of varying boundary conditions, are obtained by means of the differential analyzer. An approximate analytical method for determining the types of oscillations possible in this circuit is developed. Results obtained by this method are compared with differential analyzer solutions.

Introduction

THE BEHAVIOR of circuits involving iron-cored inductors, which saturate so that their reactances cannot be considered constant, has been studied for many years. Bethenod[1] in 1907 and Martienssen[2] in 1910 both noted that in such circuits more than one sustained value of current could be obtained for the same value of applied voltage and the same circuit parameters. The current obtained in a given case was found to depend on the way in which the phenomenon was initiated. In 1926, Mauduit[6] obtained oscillograms in which the principle component of current had a frequency which was a submultiple of the frequency of the applied voltage. Such a component of current will be referred to as a *subharmonic.* Mauduit's circuit was studied more completely by Fallou,[7] who suggested that such an arrangement could actually be used as a frequency divider.

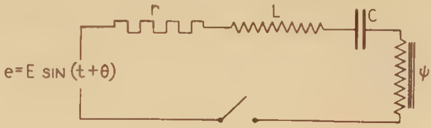
Pederson,[8] who has made a very thorough study of subharmonics in linear circuits in which the parameters vary periodically with time, also mentions the possibility of obtaining subharmonics when the inductance varies with the current.

Recently, the increasing use of series capacitors to overcome the inductive drop in transmission systems has revived interest in subharmonic oscillations. In this case it is desirable to know the range of circuit parameters for which these subharmonic oscillations can exist, and the kinds of shock excitation which may initiate them, so that they can be avoided in the engineering of series capacitor installations. This aspect of the problem was treated in some detail in a recent paper by J. W. Butler and Charles Concordia.[26]

I. Statement of the Idealized Problem

This paper is limited to considerations of the simplest known circuit which exhibits the phenomenon. This is a series circuit consisting of a constant resistance, a constant inductance, a constant capacitance, and an inductor which varies due to magnetic saturation of its core. A sine wave voltage of unvarying maximum value is impressed. This circuit is shown in figure 1.

Figure 1. Idealized circuit



The following idealizing assumptions regarding the inductor will be made:

1. The winding resistance and distributed capacitance are equal to zero.
2. All hysteresis effects in the inductor may be neglected. Hence the saturation curve is a single-valued function.
3. There are no eddy currents in the core.

Any resistance actually present in the inductor may be lumped with the external resistance. Consistent with these assumptions the voltage across the reactor may be expressed as:

$$e = \frac{d\psi}{dt}$$

where ψ is the flux linkages of the inductor. The flux linkages and the current through the inductor are related in the way expressed by the familiar *B-H* curve of a circuit containing iron. Since this relationship is an odd function, the current may be expressed by the series

$$i = a_1\psi + a_3\psi^3 + \ldots. + a_{2m-1}\psi^{2m-1} + \ldots. \tag{1}$$

The equation of the circuit is

$$ri + L\frac{di}{dt} + \frac{1}{C}\int i\,dt + \frac{d\psi}{dt} = E\sin(t+\theta)^* \tag{2}$$

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1. For all numbered references, see list at end of paper.

* The treatment in this paper is entirely mathematical; the symbols r, L, i etc., may be regarded as representing the physical quantities in any consistent unit system including per-unit.

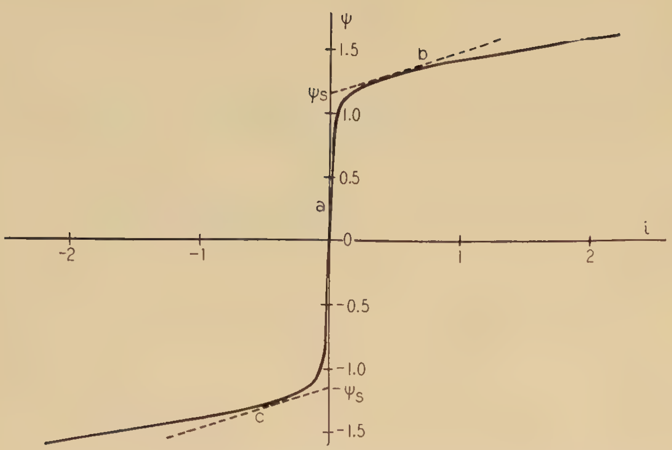

Figure 2. Experimental saturation curve and the straight-line approximation used in this paper

The problem is to determine under what conditions sustained currents of frequency lower than the impressed frequency can exist and to calculate the values of such currents.

II. The Effect of Initial Conditions in Linear and Nonlinear Circuits

The term *linear circuit* will be used to describe an electrical network the performance of which may be specified by means of a differential equation having coefficients which are not functions of the dependent variable, i.e., the coefficients are constants or functions of time only.

The term *nonlinear circuit* will be used to describe any circuit to which these conditions do not apply.

Equation 2 evidently may be transformed into a differential equation of the second order. Since ψ contains i to powers other than the first, the equation is *nonlinear.* It can be proved by application of the Lipschitz[25] condition that there exists one and only one solution of this equation corresponding to a given set of initial conditions.

Before considering the solution of the nonlinear equation let us recall the nature of the solution of a similar *linear* differential equation with constant coefficients. Here it is well known that the solution corresponding to any set of initial conditions is unique. The solution consists of two parts, a complementary function and a particular integral. In the case of a second-order equation, the complementary function contains two constants which depend upon the initial conditions whereas the particular integral is independent of the initial conditions. In equations representing practical electric circuits the complementary function dies out as time goes on, so that after sufficient time has elapsed the solution of the equation, for all practical purposes, is given by the particular integral alone. Therefore, in a circuit having constant parameters, the current which flows after a time long compared with the time constant of the circuit is independent of the initial conditions. This current is ordinarily called the *steady-state* current. That part of the current which becomes sensibly zero after a sufficient interval of time, is called the *transient* current. The division of the total current into *steady-state* and *transient* components is possible mathematically by virtue of the property peculiar to linear differential equations known as superposition.

In nonlinear equations this principle of superposition does not hold; the solution for any value of the independent variable, however large, will in general depend upon the initial conditions. Physically, this means that the current which flows in a nonlinear circuit a week after the switch was closed may depend on the phase angle of the impressed voltage at the instant of closing the switch. An example of this, in a special case where an analytical solution is possible, is given below. In many physical systems the solution after a relatively short interval of time has elapsed is periodic. It is therefore possible, by extrapolating this periodic solution back to the instant at which the phenomenon was initated, to split the solution into two parts, the periodic part which may be called a *steady state,* plus a part which dies out rapidly with time and hence might appropriately be called a *transient.*

Neither of these separate parts can be derived independently from the differential equation and the specified boundary conditions, as is possible with linear circuits. Furthermore, there is no reason to expect the periodic part to be independent of the initial conditions. This revision of the usual concept of "steady state" and "transient" is necessary if the terms are to be applied to currents which flow in nonlinear circuits.

Example Showing the Effect of Initial Conditions

Consider equation 2 in the special case when $E = 1$; $r = 0$; $\psi = Ki^{1/3}$:

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt + K\frac{d(i^{1/3})}{dt} = \sin(t+\theta) \tag{3}$$

Now let us assume the solution

$$i_a = A^3\cos^3\frac{t+\theta}{3} = \frac{A^3}{4}\left[3\cos\frac{t+\theta}{3} + \cos(t+\theta)\right] \tag{4}$$

where A is an undetermined coefficient.

Substituting the value i_a from (4) in (3) and equating coefficients of sines and cosines of like multiples of $(t+\theta)$ the following relationships can be derived:

$$K = \frac{3}{4}A^2\left[\frac{9}{C} - L\right]$$

$$4 = A^3\left[\frac{1}{C} - L\right] \tag{5}$$

Now let us assume another solution:

$$i_b = B^3\cos^3(t+\theta) = \frac{B^3}{4}\left[3\cos(t+\theta) + \cos 3(t+\theta)\right] \tag{6}$$

In the same way this gives rise to the relationships:

$$1 + KB = \frac{3}{4}B^3\left[\frac{1}{C} - L\right]$$

$$3L = \frac{1}{3C} \tag{7}$$

Any set of values of the parameters L, C, and K, which satisfies both the relationships (5) and (7) will form an equation having at least two solutions of the forms (4) and (6).

Such a set of values is:

$$L = 0.1$$

$$\frac{1}{C} = 0.9$$

$$K = 17.5$$

Equation 3 then becomes:

$$0.1\frac{di}{dt} + 0.9\int i\,dt + 17.5\frac{d(i^{1/3})}{dt} = \sin(t+\theta) \tag{8}$$

The two solutions are:

$$i_a = [-1.39\cos(t+\theta) + 0.462\cos 3(t+\theta)] \times 10^{-4} \tag{9}$$

$$i_b = 3.75\cos\frac{t+\theta}{3} + 1.25\cos(t+\theta) \tag{10}$$

That these are both solutions may be readily verified by substituting them in (8). They are entirely different in character, as one contains a term of higher frequency than the applied voltage, and the other a term of lower frequency than the applied voltage.

If the origin of time is taken as the instant when the current is passing through zero, we have for (9) the boundary conditions:

$$\theta = \frac{3\pi}{2} \qquad i_0 = 0 \qquad q_0 = 0.000124$$

The corresponding boundary conditions for (10) are:

$$\theta = \frac{3\pi}{2} \qquad i_0 = 0 \qquad q_0 = -10.0$$

If the switch were closed at the instant at which the voltage is at a negative peak and with an initial charge of -10 on the capacitor, the solution is given by equation 10. If the switch were closed at the instant at which the voltage is at a negative peak and with an initial charge of -0.000124 on the capacitor, the solution is given by equation 9. In general, if there were any other initial charge on the capacitor, or if the switch were closed at any other instant of time, a still different solution might be expected.

III. Physical Mechanism of Subharmonic Production

The physical nature of the phenomenon of subharmonic production is readily visualized if we consider the behavior of the circuit during the first few cycles after closing the switch. For simplicity let resistance be neglected, and let the boundary conditions be those of equilibrium. Let the phase angle θ be taken equal to zero. If the flux linkages in any constant inductor are included in ψ, the term $L\frac{di}{dt}$ does not appear, hence we have:

$$\frac{d\psi}{dt} + \frac{1}{C}\int i\,dt = E\sin t \tag{11}$$

from which

$$\psi = -E\cos t - \frac{1}{C}\int\int i\,dt^2 + K$$

and since for $t = 0$ we have $\psi = 0$ and $i = 0$ it follows that $K = E$, hence

$$\psi = E(1-\cos t) - \frac{1}{C}\int\int i\,dt^2 \tag{12}$$

The magnetization curve representing ψ as a function of i will be taken as shown by the solid curve in figure 2. The value ψ_s is the flux linkages at the knee of the curve.

Since the current during operation on the unsaturated portion of the ψ versus i characteristic is negligible, no appreciable current flows until $\psi = \psi_s$. From the closing of the switch until $\psi = \psi_s$ the integral $\frac{1}{C}\int\int i\,dt^2$ is therefore negligible and ψ is given nearly enough by $\psi = E(1-\cos t)$. The end of the interval during which this holds is indicated in figure 3B by T_1. The value of T_1 is given by

$$T_1 = \cos^{-1}\left(\frac{E-\psi_s}{E}\right) \tag{13}$$

Above the saturated value ψ_s the saturation curve may, to a reasonable approximation, be represented by a straight line. Let L[*] be the slope of this line and let λ be the time measured from the instant T_1. Then during the succeeding brief interval the differential equation

$$L\frac{di}{d\lambda} + \frac{1}{C}\int i\,d\lambda = E\sin(\lambda + T_1) \tag{14}$$

holds, subject to the boundary conditions:

$$\lambda = 0 \qquad i = 0 \qquad q = 0.$$

The general solution of equation 14 is:

$$i = \frac{CE}{LC-1}\sin\left(\lambda + T_1 \pm \frac{\pi}{2}\right) + A\cos\left(\frac{1}{\sqrt{LC}}\lambda + \phi\right) \tag{15}$$

For the purpose of this illustration it will be sufficient to restrict the solution to the case in which the negative sign is taken in equation 15. This corresponds to the physical case of $L > \frac{1}{C}$. Inserting boundary conditions in (15) we have

$$i = \frac{CE}{1-LC}\cos(\lambda+T_1) - \frac{1}{1-LC}\sqrt{\frac{C}{L}} \times \sqrt{LC(E-\psi_s)^2 + \psi_s(2E-\psi_s)} \times \cos\left[\frac{\lambda}{\sqrt{LC}} + \tan^{-1}\sqrt{\frac{\psi_s(2E-\psi_s)}{LC(E-\psi_s)^2}}\right] \tag{16}$$

This equation holds only until the flux linkages are reduced to the value ψ_s. At this time the current effectively stops and whatever charge has been accumulated on the capacitor is trapped there until the flux linkages again reach the value $\pm\psi_s$. During the interval from T_1 to the instant at which current stops flowing, the value of ψ is given by equation 12, in which the term $\frac{1}{C}\int\int i\,dt^2$

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[*] Note that L as used in this section is the sum of the saturated inductance of the reactor plus the external linear inductance.

must be evaluated by substitution of the proper function for i. However, after the charge is trapped on the capacitor, this term becomes $\frac{Q}{C}t$. Hence the flux linkages are given by the expression

$$\psi = E(1 - \cos t) - \frac{Q}{C}t - \psi_a \tag{17}$$

where ψ_a is the value of flux linkages corresponding to $\int\int i\, dt^2$ when current ceased to flow. It is evident that equation 17 represents an oscillatory flux linkage which has a negative component proportional to time. A value $-\psi_s$ will therefore be reached in a time which is short if Q is large and relatively long if Q is small. It is possible that Q may be so small that several cycles of the impressed frequency may have elapsed before another pulse of current occurs. *It is the trapping of charge on the capacitor which gives rise to subharmonic oscillations in circuits of this type.*

IV. Summary of Available Methods of Solution

Step-by-step methods such as that given in the preceding section are very laborious and give the solution only for the parameters and initial conditions for which they are carried out. Such methods, however, have the advantage of shedding some light on the physical nature of the phenomena which the equation describes.

The differential analyzer furnishes a very convenient method of solving equation 2. While analyzer solutions are subject to the same limitations as those obtained by the step-by-step method, in that each solution is good only for the parameters and initial conditions for which it is made, the labor of carrying out a solution is not great. Therefore, it is possible, by carrying out a large number of particular solutions, to generalize to a certain extent. A severe limitation of this method arises from the fact that the analyzer insists on giving the whole solution, including the transient, and refuses to produce a steady state until the transient has died out. In circuits in which the damping is slight, which unfortunately are those of greatest interest, this involves a considerable loss in time as well as a sacrifice in accuracy due to accumulated errors in runs of long duration.

The various other methods which have been applied to nonlinear circuits, Taylor's series expansion, isocline and other graphical methods, the analytical method of Kryloff, etc., do not seem to be of very great value in the solution of the present problem.

Recursion formulas for the boundary conditions which may produce subharmonics are developed in the appendix. This method is an extension of the method used by Boyajian[17] for calculation of this circuit when the initial conditions are such as to produce no subharmonics. The method suffers from the fact that a considerable idealization of the problem is necessary in order to carry out the mathematical details, but has the peculiar advantage, not found in other analyses of the problem, of expressing the possible steady states in terms of the circuit parameters without regard to the method of initiating the phenomenon. Although not applicable to all cases of subharmonic production, this scheme seems to be the most powerful yet developed in those cases where it applies. A combination of differential analyzer and recursion formula solutions, the differential analyzer to give the solution in the initial period and the recursion formula to give the solution after a considerable elapsed time, is perhaps the most revealing analysis possible at present.

In figure 3, a comparison of solutions by the differential analyzer, step-by-step calculations, and by the recursion formula method given in the appendix, is shown.

Figure 3*A* shows the current, applied voltage, flux linkages, and charge on the capacitor as obtained by the differential analyzer. In this case, the relation between ψ and i is that shown by the solid curve in figure 2. The other parameters are

$E = 0.7$ $\qquad L = 0.197$ $\qquad C = 4.66$

It will be noted that at time T_B all the quantities have substantially the same values as at the time T_A. Therefore, from the point T_B on, the curves will be a periodic repetition of the portion from T_A to T_B. The parts of the curves from the start to the point T_A contained *transient* portions of the solution in the sense in which the word is used in this paper. After point T_A, the solutions are *steady state* in the sense in which the term is used here.

The curves in figure 3*B* were obtained by the step-by-step method used in the preceding section to illustrate the physical nature of the phenomenon. For this calculation it was assumed that the resistance was negligible. The value of the flux linkages at the knee of the saturation curve was taken to be $\psi_s = 1.15$. The value of inductance used was the sum of the external inductance and the slope of the saturation curve above the knee; this value was taken as $0.197 + 0.303 = 0.500$. The three terms of equation 17 are shown by the dotted curves; the resultant flux linkages are shown by a solid curve. This method could be carried on indefinitely, or until at the end of some interval all the boundary conditions were found to be the same as at the end of some previous interval, in which case the remainder of the solution would of course be a repetition of the part between points of indentical boundary conditions.

In order to eliminate a prohibitive amount of piece-by-piece calculation to find repetitive boundary conditions (quite conceivably for certain circuits and initial conditions none might exist) the method worked out in the appendix is used for calculating the steady state. This yields the curves shown in figure 3*C*. The solution turns out to be a subharmonic oscillation designated in the appendix as the third kind. A comparison with the upper curves shows that the agreement with the analyzer solution is very good in spite of the idealizing assumptions made.

Appendix—Recursion Formulas for Steady State Subharmonics

In order to circumvent mathematical difficulties, resistance will be neglected in this analysis. Further it will be assumed that the

Figure 3

(*A*)—Differential-analyzer solution of the equation

$$\psi\,(i) = \int\left[0.7 \sin t - 0.05i - 0.197\,\frac{di}{dt} - 0.214 \int i\,dt\right]dt$$

(*B*)—Approximate check of analyzer solution by step-by-step calculation

(*C*)—Approximate steady-state solutions calculated from recursion relations

Scales:

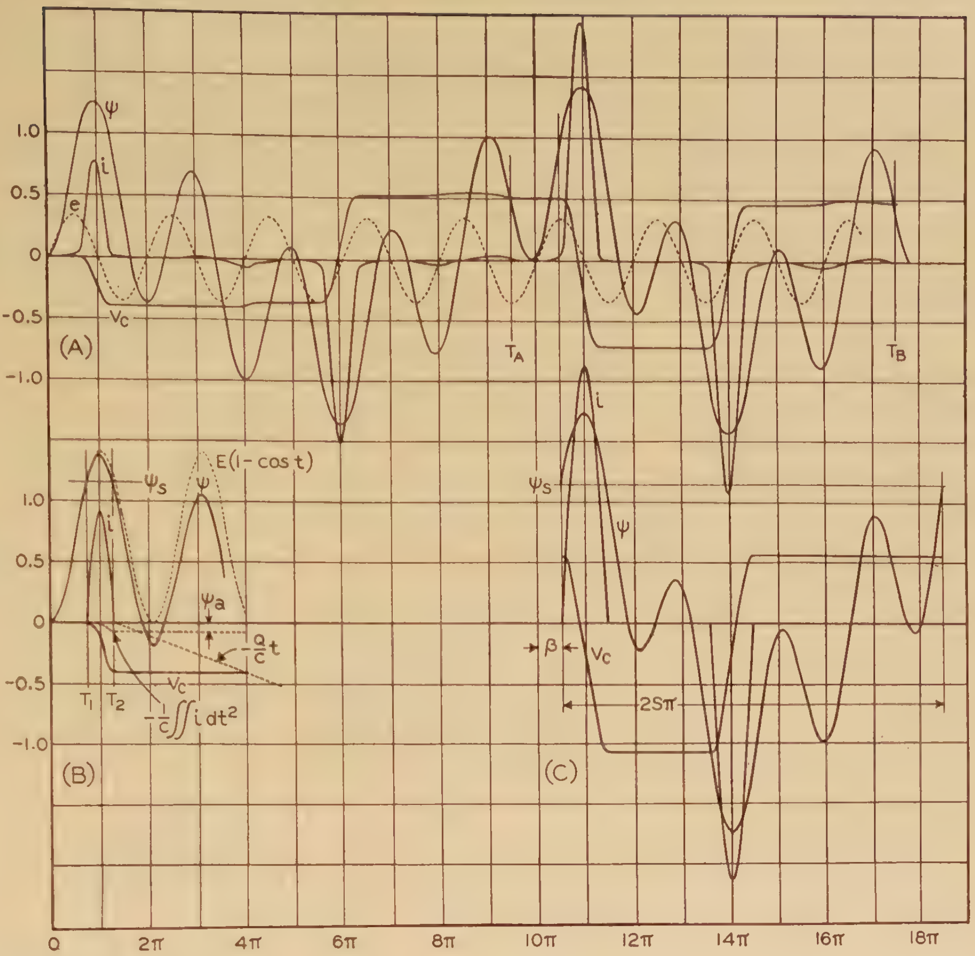
Flux linkage is shown in per unit

Time is shown in radians of the impressed sinusoid

To obtain current in per unit multiply scale shown by 0.542

To obtain capacitor voltage in per unit multiply scale shown by 0.27

Maximum value of impressed voltage is 0.7 per unit



magnetization curve of the reactor may be represented by the dotted straight lines shown in figure 2. The curve consists of three portions labled in the figure *a*, *b*, and *c*. Curve *a* consists of the ψ axis between the values $-\psi_s$ and ψ_s. For curve *b* we have $\psi = Li + \psi_s$, $i > 0$. For curve *c* we have $\psi = Li - \psi_s$, $i < 0$.

I. Operation on Curve (a)

When operation is on the ψ axis the current is zero, hence the charge is constant. The flux linkages are given by the equation

$$\frac{d\psi}{dt} + \frac{Q_0}{C} = E \sin t \tag{18}$$

Integrating

$$\psi = -E \cos t - \frac{Q_0}{C}\,t + K \tag{19}$$

in which Q_0 is the charge trapped on the capacitor at the start of operation on (*a*). If at the start $t = T_0$ and $\psi = \psi_0$, we have

$$K = \psi_0 + E \cos T_0 + \frac{Q_0 T_0}{C} \tag{20}$$

The general expression for ψ during operation on (*a*), in terms of the boundary conditions for any given traverse of (*a*), is

$$\psi = -E \cos t - \frac{Q_0}{C}\,t + \psi_0 + E \cos T_0 + \frac{Q_0 T_0}{C} \tag{21}$$

II. Operation on Curve (b) or (c)

Assume that the capacitance has small effect in comparison with the inductance when operation is on either curve (*b*) or (*c*). Then

$$L\,\frac{di}{dt} = E \sin t \tag{22}$$

and

$$q = -\frac{E}{L} \sin t + At + B \tag{23}$$

Let the boundary conditions be taken as

$$t = T_k \qquad q = -Q_k \qquad i = 0 \tag{24}$$

then we have

$$A = \frac{E}{L} \cos T_k \tag{25}$$

and

$$B = -Q_k + \frac{E}{L} \sin T_k - \frac{ET_k}{L} \cos T_k \tag{26}$$

The general expressions for the charge and current during operation on (*b*) or (*c*), in terms of the boundary conditions for any given traverse of (*b*) or (*c*), are

$$i = \frac{E}{L}(\cos T_k - \cos t) \tag{27}$$

$$q = \frac{E}{L}(\sin T_k - \sin t - T_k \cos T_k + t \cos T_k) - Q_k \tag{28}$$

III. Time Interval and Change in Charge During One Excursion in the Saturated Region

It will be assumed that when *i* becomes zero, operation on the saturated portion of the characteristic ceases (in exceptional cases this need not be true). Let T_{k+1} be the instant of time at which this occurs.

From (27)

$$\cos T_{k+1} = \cos T_k \tag{29}$$

The instant T_{k+1} occurs later than T_k, but not more than 2π later. It will be convenient to express T_k as

$$T_k = 2r\pi + \beta \qquad \text{where } -\pi < \beta < \pi \tag{30}$$

from which it follows that

$$\begin{aligned} T_{k+1} &= 2(r+1)\pi - \beta && \beta > 0 \\ &= 2r\pi - \beta && \beta < 0 \end{aligned}$$

and the time of excursion in the saturated region is

$$\begin{aligned} T_{k+1} - T_k &= 2(\pi - \beta) && \beta > 0 \\ &= -2\beta && \beta < 0 \end{aligned} \tag{31}$$

The current which flows in the saturated region and the interval for which it flows depend upon the value of β. This is shown in figure 4. The change in charge due to the current flowing during this interval may be calculated from (28):

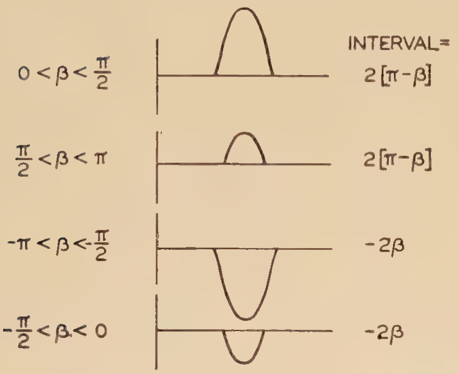


Figure 4. Types of current pulse during an excursion in the saturated region

$$\begin{aligned} Q_{k+1} &= \frac{2E}{L}[\sin\beta + (\pi - \beta)\cos\beta] - Q_k && \beta > 0 \\ &= \frac{2E}{L}[\sin\beta - \beta\cos\beta] - Q_k && \beta < 0 \end{aligned} \tag{32}$$

IV. Subharmonic Oscillation of the First Kind

One type of oscillation which may occur involves one excursion in the saturated region with positive current, one excursion down the ψ axis, one excursion in the saturated region with negative current and finally one excursion up the ψ axis to the beginning of a new cycle. Due to symmetry the charges must have the same magnitude but opposite signs in two successive excursions along the ψ axis. Such a cycle is indicated in figure 5 in which T_k has been chosen as the instant of time at which operation starts on the saturated portion of the characteristic with *positive* current. The angle β is therefore restricted to positive values.

The time interval for one complete cycle is equal to

$$T = 4(\pi - \beta) + 2\delta \qquad \beta > 0 \tag{33}$$

where δ is the time for one traverse of the ψ axis. Since for a subharmonic the period T must be given by

$$T = 2s_1\pi$$

we have

$$\delta = 2\beta + (s_1 - 2)\pi \qquad \beta > 0 \tag{34}$$

Further since the oscillation is assumed symmetrical, the angle of entrance into the negative saturated region must be an odd multiple of $\pi + \beta$. That is

$$\beta + 2(\pi - \beta) + \delta = \beta + (2n + 1)\pi$$

where $n = 1, 2, 3, \ldots\ldots$ Comparing this expression with (34) it is seen that s_1 must be an odd integer. Oscillations of this kind are all *odd* subharmonics. Equation (32) gives the value of Q_k in terms of the angle β if we impose the condition $Q_{k+1} = Q_k$ (since $-Q_k$ was taken as the charge during travel up the ψ axis),

$$Q_k = \frac{E}{L}[\sin\beta + (\pi - \beta)\cos\beta] \tag{35}$$

If the boundary conditions corresponding to one travel up the ψ axis are inserted in (21) we have

$$\begin{aligned} \psi_0 &= -\psi_s && \psi = \psi_s \\ Q_0 &= -Q_k && t = 2r\pi + \beta \\ T_0 &= (2r - s_1 + 2)\pi - \beta && \beta > 0 \end{aligned}$$

$$2\psi_s = E[\cos(\beta + s_1\pi) - \cos\beta] + \frac{Q_k}{C}[2\beta + (s_1 - 2)\pi] \tag{36}$$

Substituting (35) in (36), we have

$$\frac{2LC\psi_s}{E} = -2LC\cos\beta + [2\beta + (s_1 - 2)\pi][\sin\beta + (\pi - \beta)\cos\beta] \tag{37}$$

The alignment chart figure 6 gives solutions of this equation for various values of the parameters. In this chart

$$A = \frac{2LC\psi_s}{E} \qquad B = 2LC \qquad m = s_1 - 2$$

The dotted line in figure 6 gives a representative solution. In this case $A = 5.75$ and $B = 5$. For $m = 1$, we have two values of β, 10° and 102°. For $m = 3$, we have one value of β, 134°, etc.

V. Subharmonic Oscillation of the Second Kind

Another type of oscillation encountered experimentally is that shown in figure 7. This type corresponds to the route over the saturation curve outlined in the figure. In this case the charge $-Q_k$ which exists at the instant T_k, is removed due to the flow of current

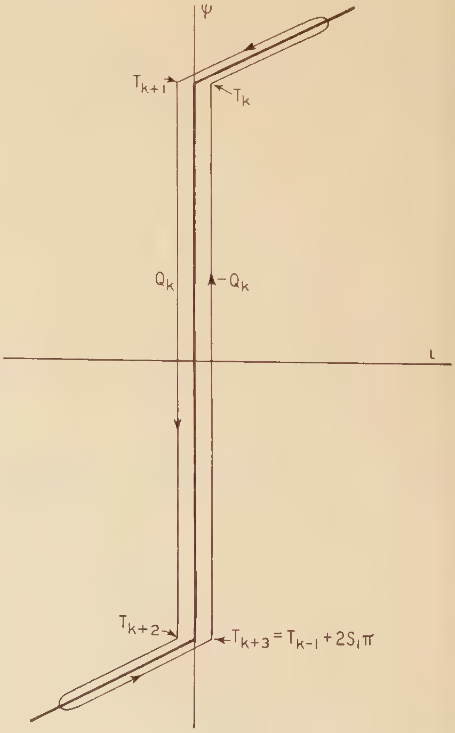


Figure 5. Path of subharmonic oscillation of the first kind

in the interval $(T_{k+1} - T_k)$, so that during the interval $(T_{k+2} - T_{k+1})$ the charge on the capacitor is zero. The value of the order s_2 of the subharmonic may be calculated as follows:

Half period $= (T_{k+4} - T_k) = (T_{k+4} - T_{k+3}) + (T_{k+3} - T_{k+2}) + (T_{k+2} - T_{k+1}) + (T_{k+1} - T_k)$

$$s_2\pi = 2\beta + (s_1 - 2)\pi + 2(\pi - \beta) + 2\beta + 2(\pi - \beta)$$

Hence s_2 is equal to $(s_1 + 2)$; s_2 is therefore an odd integer.

In the first type of oscillation the charge is reversed each time current flows; in the oscillation of the second kind the first pulse of current after an excursion along the ψ axis reduces the charge to zero and the second pulse charges the capacitor to a value equal and opposite to the original charge. Therefore equation 35 must be rewritten

$$Q_k = \frac{2E}{L}\,[\sin\beta + (\pi - \beta)\cos\beta] \qquad (38)$$

Equation 36 remains unchanged. However we wish to express (36) in terms of s_2:

$$2\psi_s = E\,[\cos(\beta + s_2\pi) - \cos\beta] + \frac{Q_k}{C}\,[2\beta + (s_2 - 4)\pi] \qquad (39)$$

Substituting (38) in (39) we have:

$$\frac{LC\psi_s}{E} = -LC\cos\beta + [2\beta + (s_2 - 4)\pi][\sin\beta + (\pi - \beta)\cos\beta] \qquad (40)$$

Solutions for various values of the parameters are given by the alignment chart figure 6. In this chart

$$A = \frac{LC\psi_s}{E} \qquad B = LC \qquad m = s_2 - 4$$

VI. Oscillation of the Third Kind

It sometimes happens, as in figure 3, that the condenser charge accumulated during the transient causes the two portions of a cycle to be unsymmetrical. As before let T_k be the instant of time at which operation starts on the positive saturated portion of the characteristic. The charge during the interval preceding T_k was $-Q_k$. During the interval $T_{k+1} - T_k$ the negative charge is removed and a *greater* positive charge Q_{k+1} is put on the condenser. Hence we have

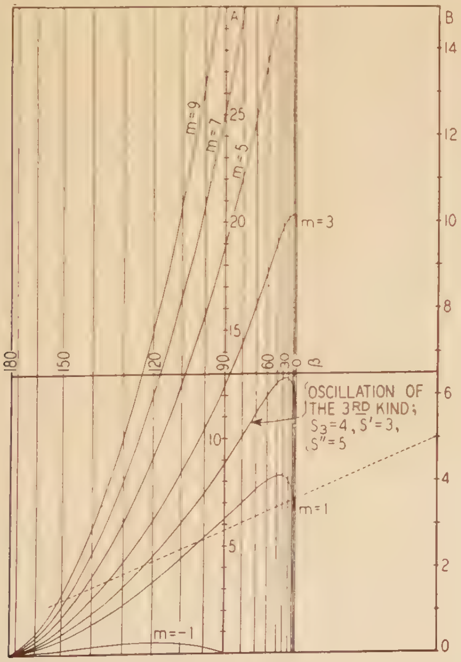


Figure 6. Alignment chart for the equation

$$A + B\cos\beta - (2\beta + m\pi)\,[\sin\beta + (\pi - \beta)\cos\beta] = 0$$

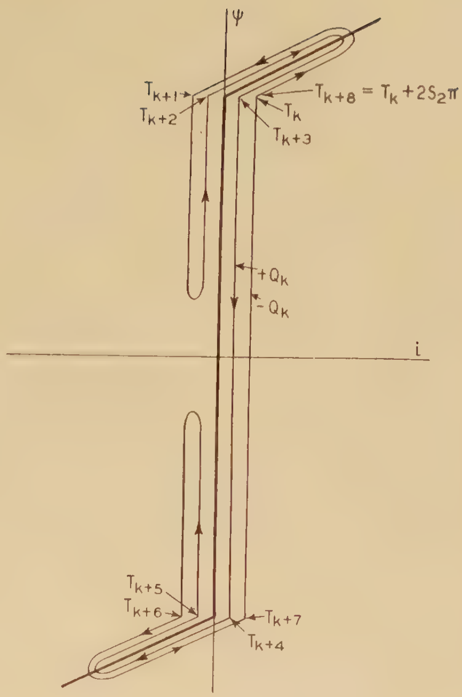


Figure 7. Path of subharmonic oscillation of the second kind

$$Q_k + Q_{k+1} = \frac{2E}{L}\,[\sin\beta + (\pi - \beta)\cos\beta] \qquad (41)$$

If the two current pulses are to be the same, we have

$T_{k+2} - T_k = \beta + s'\pi$ where s' is an odd integer (42)

and also

$T_{k+4} - T_{k+2} = \beta + s''\pi$ where s'' is also an odd integer (43)

If $Q_{k+1} > Q_k$, as assumed, then s' which includes a passage along the ψ axis with charge Q_{k+1} will be smaller than s'' which includes a passage along the ψ axis with a charge of Q_k; we have

$$2(\pi - \beta) + \delta' = s'\pi$$
$$2(\pi - \beta) + \delta'' = s''\pi$$

where δ' and δ'' are the two time intervals on the ψ axis.

$$\delta' = 2\beta + (s' - 2)\pi \qquad (44)$$

$$\delta'' = 2\beta + (s'' - 2)\pi \qquad (45)$$

The flux linkage equations become

$$2\psi_s = -2E\cos\beta + \frac{Q_k}{C}\,[2\beta + (s'' - 2)\pi] \qquad (46)$$

$$2\psi_s = -2E\cos\beta + \frac{Q_{k+1}}{C}\,[2\beta + (s' - 2)\pi] \qquad (47)$$

If we let Δ be the unbalanced charge and Q be the charge which is reversed at each current pulse we have

$$Q_k = Q - \Delta$$
$$Q_{k+1} = Q + \Delta \qquad (48)$$

Subtracting (46) from (47), it follows that

$$\Delta = \frac{(s'' - s')\pi Q}{2[2\beta + (s_3 - 2)\pi]} \qquad (49)$$

in which $s_3 = \dfrac{s' + s''}{2}$ is the order of the subharmonic.

Q may be obtained from (41), hence

$$\Delta = \frac{(s'' - s')\pi E[\sin \beta + (\pi - \beta) \cos \beta]}{2L\,[2\beta + (s_3 - 2)\pi]} \tag{50}$$

Adding (46) and (47), we obtain

$$\psi_s + E \cos \beta = \frac{[2\beta + (s_3 - 2)\pi]Q}{2C} + \frac{(s' - s'')\pi}{4C} \tag{51}$$

Hence

$$\frac{2LC\psi_s}{E} + 2LC \cos \beta = [2\beta + (s_3 - 2)\pi][\sin \beta + (\pi - \beta) \cos \beta] - \frac{\pi^2(s'' - s')^2\,[\sin \beta + (\pi - \beta) \cos \beta]}{8[2\beta + (s_3 - 2)\pi]} \tag{52}$$

Comparing (52) with (37) it is seen that the solution for oscillations of the third kind is like that for oscillations of the first kind except for the correction term due to Δ. When s'' is equal to s' (52) reduces to (37) as should be expected.

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Discussion

Ernst Weber (Polytechnic Institute of Brooklyn, Brooklyn, N. Y.): In explaining the production of subharmonics in circuits containing iron-cored inductors the authors employ, in addition to the differential-analyzer attack, two phases of theoretical attack. The more important and most interesting one is the region-by-region method, substituting three straight lines for the nonlinear characteristic of the iron-cored inductor. Particularly happy is the concept of the "trapped" charge on the condenser which is amply confirmed by the results obtained with the differential-analyzer.

Less convincing is the attempt to show by a direct analytical attack the effect of initial conditions upon the "steady state" response of the nonlinear circuit. The circuit analyzed consists of a capacitance C in series with a linear inductance L and a nonlinear inductance of flux linkages $\psi = Ki^{1/3}$, and having an applied voltage 1.sin $(t + \theta)$, the time measured in radians. The circuit is treated as nondissipative, that is, disregarding resistances and this feature invalidates most of the reasoning. In order to show that the analysis cannot be valid, let us apply the authors' reasoning to a linear circuit of the same type. Then the flux linkages ψ can be expressed as $\psi = K.L$ and, in differentiating, can be combined with the first term Ldi/dt so that one obtains

$$(L + K)\frac{di}{dt} + \frac{1}{C}\int i\,dt = \sin(t + \theta) \tag{1}$$

Assume now that the solution of (a) consists of an n'th harmonic current in addition to the current of impressed frequency,

$$i_a = A \cos(t + \theta) + B \cos n(t + \theta) \tag{2}$$

where A and B are undetermined coefficients. Substitution of (2) and equating coefficients of sines of like multiples of $(t + \theta)$ leads to the two conditions:

$$\left.\begin{aligned} B \cdot \left[n(L + K) - \frac{1}{nC}\right] &= 0 \\ A \cdot \left[\frac{1}{C} - (L + K)\right] &= 1 \end{aligned}\right\} \tag{3}$$

Obviously the first condition (3) can be satisfied by letting the term in brackets vanish, that is, choose

$$(L + K) = \frac{1}{n^2C} \tag{4}$$

giving

$$A = \frac{n^2C}{n^2 - 1}$$

so that the solution finally is

$$i_a = \frac{n^2C}{n^2 - 1}\cos(t + \theta) + B \cos n\,(t + \theta) \tag{5}$$

where B can take any value whatsoever. What is the meaning of two frequencies in this steady-state solution for a linear circuit with single impressed frequency?

The explanation lies in the following facts: (1) resistance has been disregarded; (2) the parameters have been chosen to satisfy the resonance condition (4) for the n'th harmonic, making this a proper frequency of the circuit; (3) in a nondissipative circuit zero voltage can produce a current of arbitrary magnitude if resonance exists; (4) in a nondissipative circuit the application of any voltage initially different from zero will excite a steady a-c current of the proper frequency which can persist indefinitely.

Now, the authors follow in the case of their nonlinear circuit exactly the same procedure as outlined above for the linear circuit. Since they assume for the flux linkages the law $\psi = Ki^{1/3}$, the introduction of the third harmonic (sub- or super-) is natural. Their solution does, therefore, *not* give the steady-state term but includes an involuntary a-c steady transient term as well. The nonlinearity hides this fact, particularly since the amplitude of the harmonic must have a special value in order to be able to satisfy the nonlinear differential equation. The conclusion of the authors that there can exist entirely different characteristic responses to an applied a-c voltage for different switching angles is not justified. In fact, experience shows that the final steady state as seen in oscillograms is typically the same for various switching angles, though not necessarily of exactly the same form. Otherwise any practical use of the relay circuits based upon the critical features of the ferroresonant element would be incomprehensible.

I. A. Travis and C. N. Weygandt: Doctor Weber shows that in a linear circuit with an applied voltage there can exist two sustained sinusoidal components of current having different frequencies, if resistance be neglected. One of these components has the frequency of the applied voltage whereas the other has a frequency dependent on the inductance and capacitance in the circuit but *not* dependent in any way upon the initial conditions. The initial conditions determine the maximum value of this component but do not influence the frequency.

In the nonlinear circuit given in part II of the paper there can be many solutions involving many frequencies. Of these we give two, which happen to be readily expressible in trigonometric form. The essential thing is that these solutions show that in a circuit with a given capacitor and nonlinear inductor, components of current having entirely different frequencies may flow depending on the initial conditions. Thus equation 9 is a solution containing a fundamental and a third harmonic, while equation 10 is a solution for the same circuit containing a fundamental and a one-third harmonic. In a given single mesh linear circuit such as that described by Doctor Weber it is impossible to get more than one frequency in addition to that of the applied voltage and this frequency is never dependent upon the initial conditions. The only special attribute of the one-third power with reference to these two solutions is that they are the only two expressible in simple form. Many other solutions were actually obtained on the differential analyzer, which had frequencies in no way related to the number three.

The question as to whether or not the solutions (9) and (10) contain "involuntary steady transient" terms, which might die out if resistance were considered is one which the authors cannot answer. The whole question of stability of subharmonics is one with which the present investigation did not concern itself. It is, however, believed that circuits having resistance exist in which can flow currents of frequency dependent on the initial conditions, and which so far as oscillographic study is concerned have every right to the name steady state.

Recovery-Voltage Characteristics of Typical Transmission Systems and Relation to Protector-Tube Application

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Introduction

THE SUCCESSFUL operation of an arc-interrupting device requires that the insulation recovery-voltage characteristics of the device be higher than the recovery-voltage characteristics of the system. A broad understanding of the recovery-voltage problem from the application point of view, requires a knowledge of the effects caused by the range of systems, by the different types of faults and the different fault conditions encountered in practice. With this object in mind an investigation was undertaken to provide a general picture of the recovery-voltage characteristics of transmission systems.

In order to carry out this investigation consideration was given to the several possible modes of attack which include analytical, field-test, and a-c calculating-board methods. Analytical methods are of limited value for such a study because of the involved nature of the problem, the range of conditions, and number of cases which must be considered. Field tests, although providing results of value as benchmarks, are of restricted use because it is impractical by this means alone to study an adequate number of conditions with suitable range of system constants and fault conditions. Because of these limitations in analytical and field-test methods, this investigation has been carried out by the a-c calculating-board method, described by the authors in a recent paper.[1]

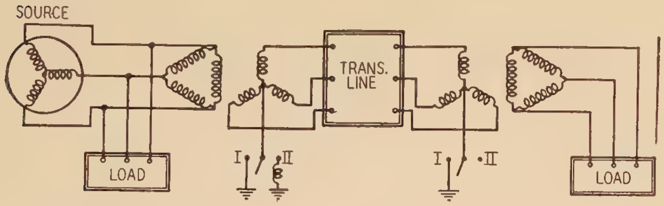

Figure 1. Schematic diagram of system selected for study

Group I—Solidly grounded at both ends. Used for curves of figure 6
Group II—Reactance grounded at sending end; ungrounded at receiving end. Used for curves of figure 7

It is proposed in this paper to present the results of general analyses made on a number of typical transmission systems subjected to faults of such a type that their clearing restores the systems to the original circuit conditions. This type of fault does not include the ordinary circuit-breaker sectionalizing operation but it does include the protector tube and many "shunt" type applications with circuit breakers or fuses whose operations do not change the main circuit condition. It is also proposed to illustrate the use of the results of such recovery-voltage studies with the application of protector tubes and to discuss the operating experience with certain typical applications. Although the usefulness of this general study will be illustrated by only one specific application the authors believe that it has a definite use in connection with other applications.

Part I

Systems Selected for Analysis

A broad perspective of the recovery-voltage problem can be obtained from the study of a representative set of systems. For this purpose three-phase, 60-cycle systems with transmission lines of the three voltage classes, namely, 34.5, 69, and 138 kv were selected. Since the recovery voltage of a system is materially affected by the length of connected line, the lengths were selected to represent the shortest that would be encountered at that particular voltage for the large majority of systems. These selections were as follows: 22.5 miles for 34.5 kv, 45 miles for 69 kv, and 90 miles for 138 kv. Although it was recognized that more than one circuit would be required to transmit the maximum amount of power a single-circuit line was used because this gives the more severe recovery-voltage conditions.

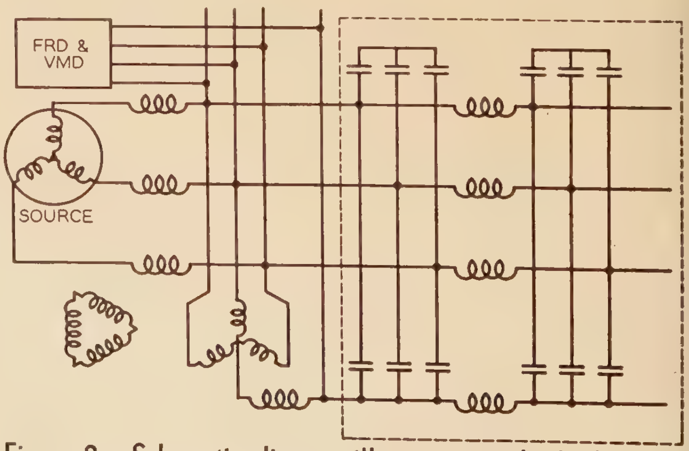

Figure 2. Schematic diagram illustrating method of system representation used on the a-c calculating board

FRD—Fault-representation device *VMD*—Voltage-measuring device

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1. For all numbered references, see list at end of paper.

Table I. Characteristics of System Selected for Study

Voltage	34.5 Kv	69 Kv	138 Kv
Short-Circuit Amperes			
(*a*)	500	500	500
(*b*)	2,000	2,000	1,000
(*c*)	6,000	6,000	4,000
Short-Circuit Kva			
Load kva	5.0	4.0	3.0
Line length (miles)	22.5	45	90

The general features of these systems are shown schematically in figure 1. For each voltage class three different conditions were assumed, each having different values of generating capacity and load. Table I gives the symmetrical three-phase short-circuit current that would be encountered for a "bolted fault" at the sending end. Systems capable of supplying the higher short-circuit currents have in general larger connected loads. Table I gives the ratio of short circuit kilovolt-amperes to load kilovolt-amperes that was used in this study. Both no-load and loaded conditions were considered. An 80 per cent power factor load was divided equally between the generator bus and the receiver bus as shown in figure 1.

The generating and transformer capacities were proportioned to the load for the particular system and short-circuit current, and typical constants were assumed for all of the system elements. Transmission lines without ground wires were chosen. The additional complication to take care of the cases with ground wires is not warranted because the problems are similar and also the recovery voltages are less severe when ground wires are used.

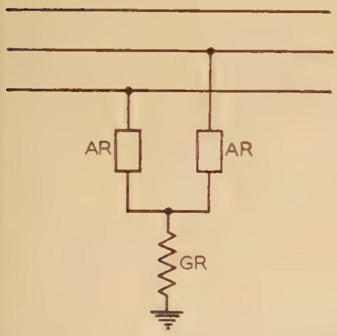

Figure 3. Connection diagram for double line-to-ground fault

AR—Arc-representation device
GR—Ground or tower-footing resistance

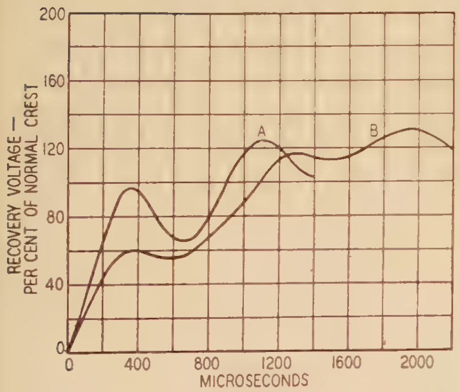

Figure 4. Examples of Cartesian plot of polar oscillograms taken during general studies

A—Single line-to-ground fault at sending end. 138-kv solidly grounded system having 1,000 amperes symmetrical three-phase short-circuit current, zero tower-footing and arc resistance, and load

B—Double line-to-ground fault at sending end. 138-kv solidly grounded system having 500 amperes symmetrical three-phase short-circuit current, 33.0 ohms tower-footing resistance, zero arc resistance, and load

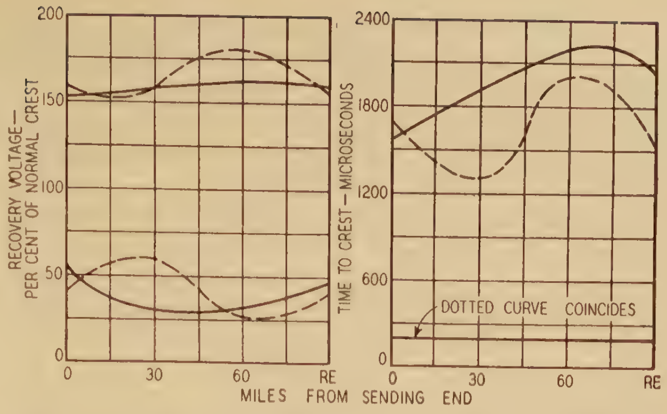

Figure 5. Recovery voltage for first and maximum crests and time to first and maximum crests as a function of location of fault on 90-mile solidly grounded 138-kv system supplying 826 amperes symmetrical three-phase short-circuit current at sending end

——— Single line-to-ground fault, no tower-footing or arc resistance
– – – – Double line-to-ground fault, 33.0 ohms tower-footing resistance

Variable Factors Considered in the A-C Board Study

In making the general analysis the factors that were varied were method of grounding, load, type of fault, fault resistance, arc resistance, and location of fault. The studies can conveniently be divided into two groups with respect to the method of grounding, namely: Group I with system solidly grounded both at sending- and receiving-end transformers, and group II with the system grounded through a reactance at the sending end only. The solidly grounded systems, of group I, were studied for both single line-to-ground and double line-to-ground faults and for fault or tower-footing resistance of 0, 25, and 100 ohms, and with and without resistance for arc representation. The effect of load was investigated by comparing the results of the above tests with results of a few tests made without load and without fault or arc resistance. The second set of tests for the reactance-grounded system, group II, was made with the addition of a neutral reactor of such magnitude as to make the zero-sequence reactance at the sending end equal to 8.5 or 34 times the zero-sequence reactance of the supply transformer.

Connection and Adjustment of the A-C Calculating Board

The method of connecting the a-c calculating board is illustrated in figure 2. The actual connection and adjustment of the board was similar to that described in the paper[1] referred to previously. The selected systems were set up in miniature on a three-phase basis and the fault was applied and removed by means of the commutator. The commutator is designed to allow adjustment of the point of initiating the fault and removing it, and arc characteristics can be simulated in the circuits. The transient voltages are measured by a cathode-ray oscilloscope and the records secured on a rotating film.

In figure 2 the transmission line is shown by a simple pi representation but actually experience and judgment must be used in determining whether this simple representation or one with more branches should be used for any specific study. For the majority of studies the forced and natural frequencies used were those of the actual system. However, for some systems which involve relatively high natural frequencies it may be advantageous to use lower frequencies and apply proper corrections. The need for such a procedure depends upon the relative losses of the miniature and the actual systems. In this particular set of investigations it was necessary to use this procedure for the lower-voltage systems. Another network representation problem was encountered with systems having relatively low source inductance. In this case the transients had relatively large amounts of energy associated with the higher-frequency components and adjustments were required to compensate for the increased attenuation.

The general procedure of making adjustments and obtaining the recovery voltage has been described in the previous paper. The manner in which fault and arc resistances were introduced in the circuit for the case of the double line-to-ground fault is illustrated in figure 3. The point of application of the fault was selected and the fault duration was modified so that each phase would clear at its earliest normal current zero. The point of application of the fault was then shifted successively until the maximum recovery voltage of either phase was obtained. It is data secured in this manner that are plotted in the curves given in a subsequent section. The scope of this study

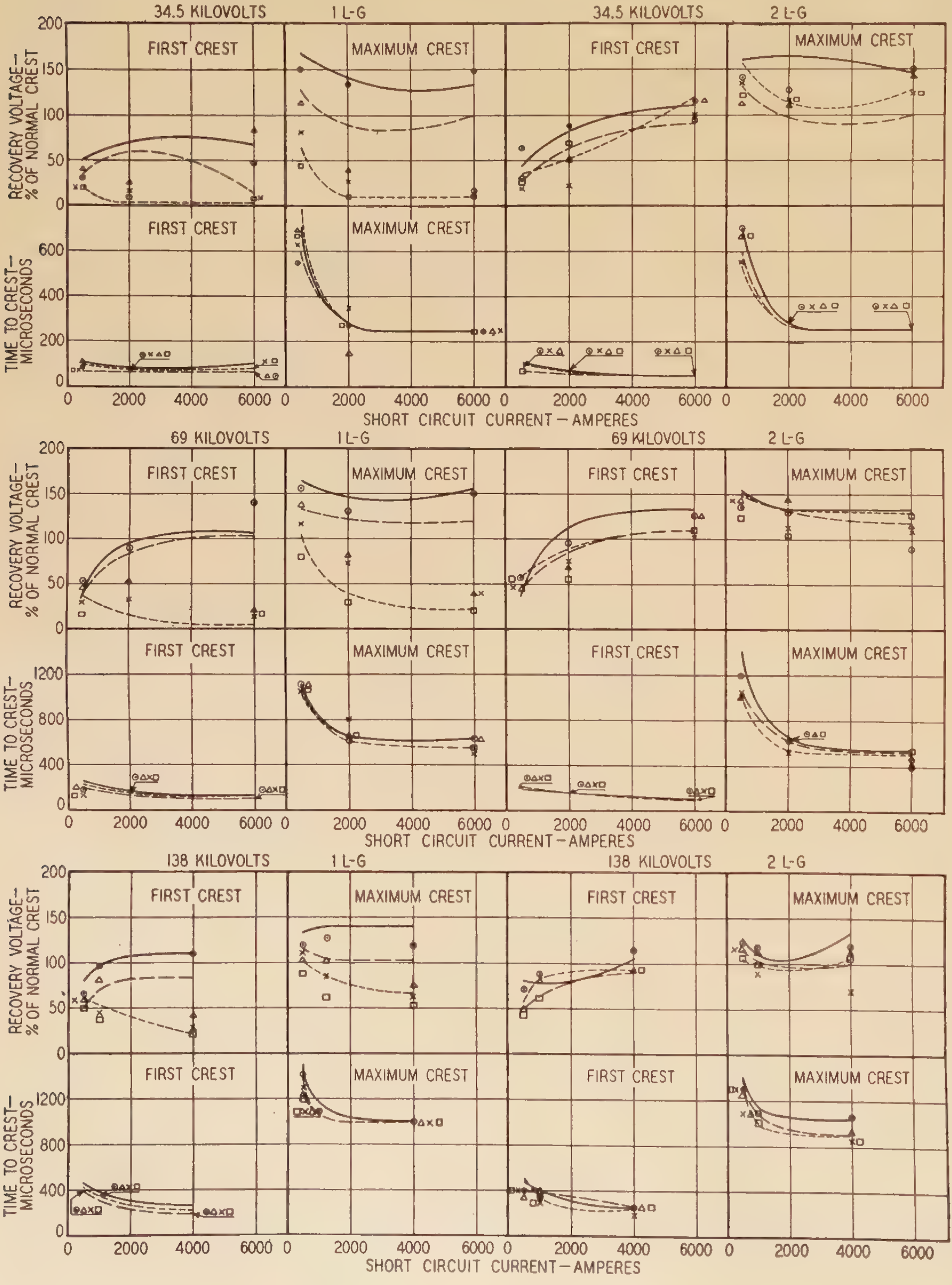

Figure 6. Recovery voltage curves and plotted points for the nine selected systems

Group I—Solid grounding. Voltage magnitude and time to crest plotted as a function of three-phase symmetrical short-circuit current at the sending end

Notation: 1-*L*-*G*, single line-to-ground fault; 2-*L*-*G*, double line-to-ground fault

	Load	Arc Resistance	Tower-Footing or Ground Resistance (Ohms)
——	Yes	No	0
— —	Yes	Yes	0
- - -	Yes	No	100
⊙	Yes	No	0
Δ	Yes	No	25
X	Yes	Yes	25
□	Yes	Yes	100

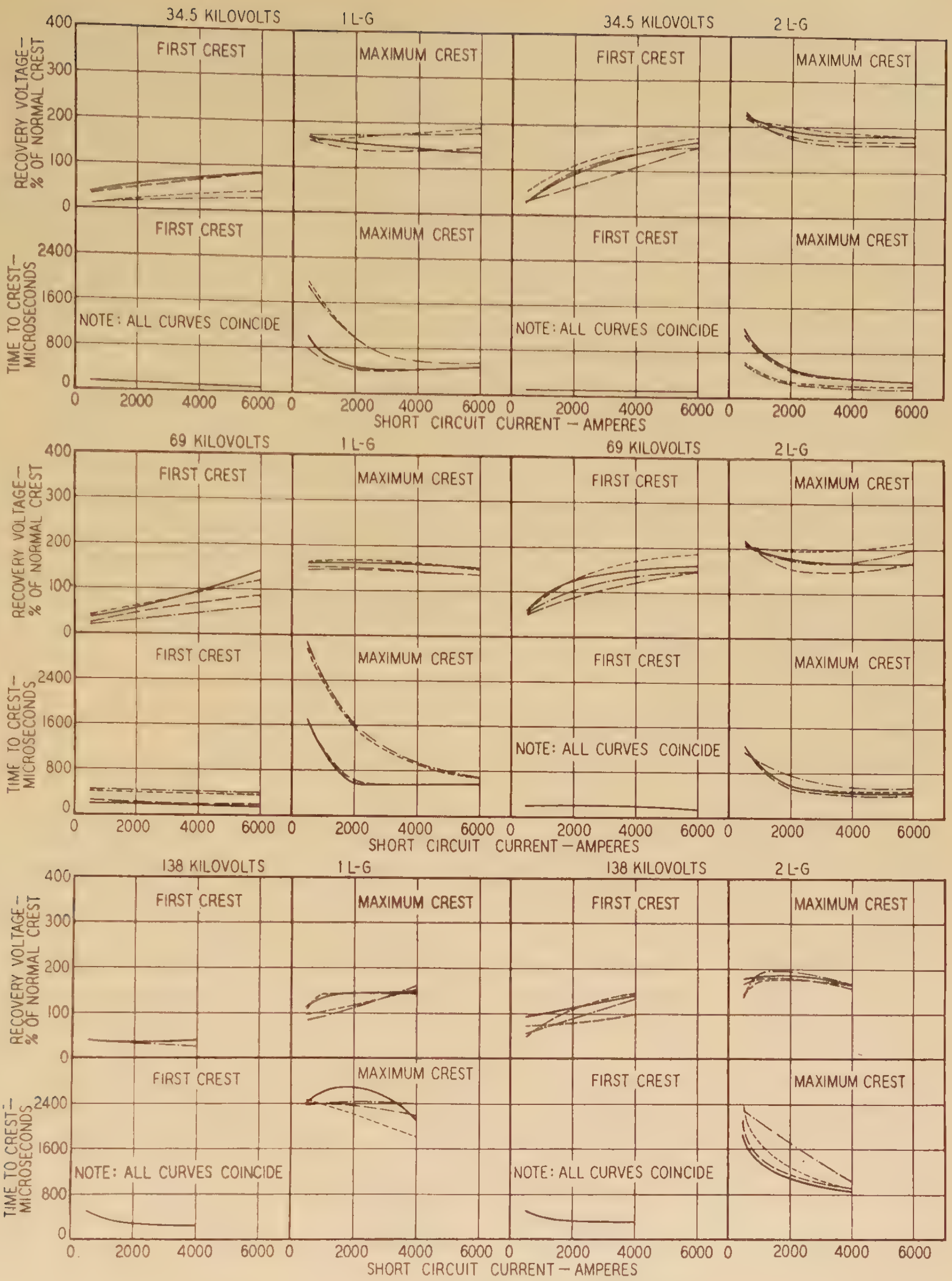

Figure 7. Recovery-voltage curves

Group II—Reactance grounding. Voltage magnitude and time to crest plotted as a function of the three-phase symmetrical short-circuit current at the sending end

Notation: 1-*L*-G, single line-to-ground fault; 2-*L*-G, double line-to-ground fault

	Reactance Value	Arc Resistance
————	Low	No
– – – –	Low	Yes
— - —	High	No
— — —	High	Yes

was limited to the cases in which the faults were cleared at normal current zero without restriking of the arc.

Typical recovery-voltage curves obtained from the a-c calculating-board study are plotted in figure 4. These curves show definite first crest and maximum crest. In some cases, second and third crests were of approximately the same magnitude, and in these cases the second crests were used as they are more severe for an insulation-recovery curve that has a rising slope.

Results of A-C Calculating-Board Studies

In an investigation of this type it is not practical to consider the application of the fault at several points on the system. A preliminary study was, therefore, made to determine the effect of moving the fault along the line. Figure 5 shows the results of such a study for a 90-mile, 138-kv system capable of supplying a symmetrical three-phase fault current of 826 amperes at the sending end and with no load on the system. The recovery-voltage results for the single line-to-ground fault are for zero tower-footing resistance and the results for the double line-to-ground fault are for 33-ohm tower-footing resistance. When it is considered that both time and magnitude are of importance in studying the effect of recovery voltage on a piece of apparatus, it will be seen that although the magnitude varies as the fault is moved along the line, the time also varies. Considering the shape of insulation-recovery voltage curves for certain specific pieces of apparatus, it was concluded that the recovery-voltage conditions were about as severe for faults at the sending end as at any location along the line. Therefore, the fault at the sending end was considered to be representative and was used in the general studies.

Based on the selected systems, a series of studies was made on the a-c calculating board to determine the effect

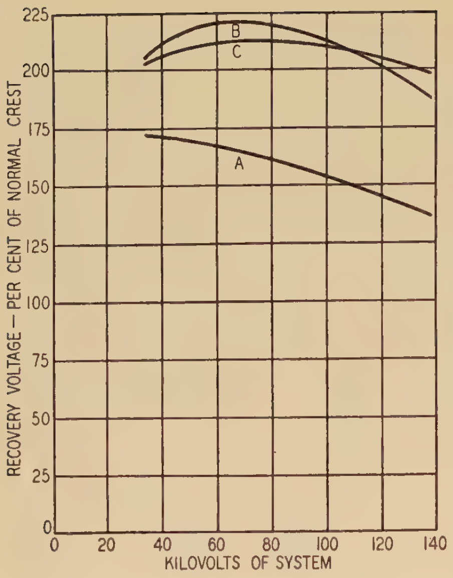

Figure 8. Envelope of maximum recovery voltages for different system-grounding conditions

A—Solidly grounded system
B—Low-reactance ground at sending end
C—High-reactance ground at sending end

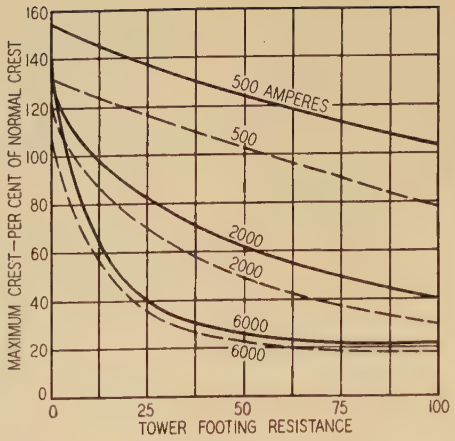

Figure 9. Maximum recovery voltage for different symmetrical three-phase short-circuit currents at sending end, plotted as a function of tower-footing resistance for single line-to-ground fault on 69-kv solidly grounded system

——— No arc resistance
– – – – With arc resistance

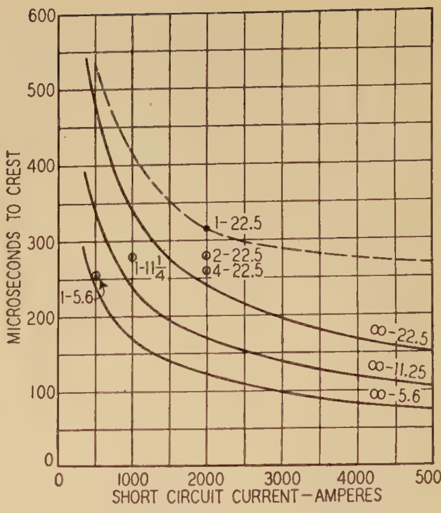

Figure 10. Recovery-voltage time to crest for 34.5 kv system plotted as a function of symmetrical three-phase short-circuit current

——— Infinite number of lines of different lengths
– – – – Finite number of lines aggregating 22.5 miles

Example: Notation 1–22.5. First figure—number of circuits; second figure—aggregate miles of line

of the different factors entering into the recovery-voltage problem. These studies may be divided into two groups; group I for the solidly grounded neutral systems, and group II for the reactance-grounded systems, described in connection with figure 1. The results of these studies are presented in figures 6 and 7, respectively. Referring to figure 6, it will be seen that for each voltage class studied the times to first crest and to maximum as well as the magnitude of the first crest and the maximum are presented for the single line-to-ground and double line-to-ground fault cases. For these curves the abscissa is the current magnitude for a symmetrical three-phase short circuit at the sending end. The results for a system under load are plotted for each current condition, with and without the arc representation device for 0-, 25,- and 100-ohm tower-footing resistance. For comparison, one study with no load and zero arc and tower-footing resistance is plotted. The arc representation device is of the same general type as described in the previous paper making use of Rectox resistors to simulate the arc characteristics of a deion protector tube. The Rectox resistor was adjusted to give approximately 20 per cent of line-to-neutral voltage at the peak of the symmetrical short-circuit current wave. This value was chosen to give the maximum effect of this factor as the minimum effect is shown by the condition of load and no arc representation device.

Figure 7 presents the results of similar studies made on the same systems except with reactance grounding. The system arrangement with respect to grounding is shown in figure 1.

The recovery-voltage data in figures 6 and 7 can be plotted in a large number of ways, depending upon the point under investigation. It is of general interest to know the maximum recovery voltage that can be encountered on a system when all the factors are varied. Figure 8 shows a plot of the envelope of such maximum values. Figure 9 shows another manner in which the data can be plotted. This example is for the 69-kv solidly ground system with load and with and without the arc representation device. It will be seen from figure 6 that the time to crest for different fault-resistance values does not change materially so that the significant factor is magnitude as plotted. This curve has been included to emphasize the fact that the introduction of tower-footing resistance reduces the recovery-voltage magnitude for a single line-to-ground fault.

A general review of the results of these studies is of interest. The introduction of load has little effect although it reduces the magnitude and decreases the time to crest slightly. The introduction of arc resistance in the solidly-grounded system reduces the magnitude for both single and double line-to-ground cases but very materially for the former. The time to crest is not influenced very much. Tower-footing resistance lowers the magnitude and the greater the resistance the larger this effect. Again the time is not affected.

Reactance grounding materially increases the magnitude. The introduction of resistance tends to lower the magnitude for both values of reactance grounding but the effect is not marked. The time to maximum crest for the single line-to-ground fault is considerably increased with the introduction of reactance.

On the solidly-grounded neutral system the magnitudes are very close for the single and double line-to-ground faults. For the reactance-grounded systems the magnitude of the double line-to-ground fault is considerably higher than for the single line-to-ground case.

When a comparison of the results of the tests on systems with line connected is made with the severity of tests for circuit breakers,[2] it is found that the magnitudes are lower. The largest difference is in the time to crest, this being 6 to 12 times as much as for the circuit-breaker test. If the aggregate length of line is increased over the values used in the studies, the spread in the time to crest will be still greater. The effect of line is, therefore, very important in the recovery-voltage problem. It is also of interest to note that the envelope of maximum magnitudes decreases for the higher system voltages as a result of the greater lengths of connected lines.

Since the system recovery voltage has a decided bearing on the economical design of the protector tube and since the laboratories for testing circuit breakers give more severe recovery voltages than found on actual systems, we believe the data presented will be very useful in the preparation of a test code for protector tubes. Such requirements might be specified as magnitude of recovery voltage and time to crest for given short-circuit currents.

Effect of Other Factors

Although a large number of different factors have been investigated for different fault conditions and different conditions of grounding in the a-c calculating-board studies, there are, nevertheless, certain other pertinent factors that enter into an application which must be considered. The analytical method of solution is useful in considering some of these factors, such as the number of circuits and their total capacitances, the latter being proportional to the aggregate length of line. In order to illustrate the effect of *total capacitance* or aggregate length of line, figure 10 has been prepared and it shows that the time to crest is very materially affected. For example, for the case of a system capable of supplying a symmetrical three-phase short-circuit current of 2,000 amperes and with the capacitances equivalent to 5.6 miles of line lumped at the sending end, the time to crest is approximately 120 microseconds whereas with the capacitances of 22.5 miles of line lumped at the sending end the time to crest is approximately 240 microseconds. It is seen that the severity increases with the decreased aggregate length of line and approaches a maximum severity with zero line, which is the case for the circuit-breaker sectionalizing application. The time to crest for a single-phase circuit is equal to $\pi \sqrt{LC}$, where L corresponds to the source inductance and C to the total capacitance assumed lumped at the sending end, and line reactance is neglected. If the time to crest for a given short-circuit current and aggregate length of line is known, the time to crest for any other length of line would increase approximately as the square root of the ratio of the aggregate line lengths.

The effect of *length of line*, that is straightaway length as contrasted with aggregate length, is brought out in figure 10. The condition of capacitance being lumped at the sending end for 22.5 miles of line is plotted and compared with the effect of a single line 22.5 miles long. This, in effect, shows the range of time that can be expected for a given aggregate length of line for anything from a single to an infinite number of lines. Points are also shown for two and four lines for the 2,000-ampere condition. It will be seen that when length is increased the time to crest is increased. The severity of recovery voltage is inversely proportional to the times to crest given in figure 10 as the magnitude remains practically constant for this case.

Figure 11 shows the results of a number of calculations[1] based on the wave theory, for the nine selected systems previously studied. These calculations are made for single line-to-ground faults at the sending end with the sending and receiving ends solidly grounded. These do not consider the effects of load, initiating transients, or tower-footing or arc resistance. They do, however, illustrate the general shape of the recovery-voltage curve and give a close check for the a-c calculating-board studies for maximum crest. In the curves of figure 11 the magnitude of the "first crest" at the shorter times is also of interest as it is probably a lower limit of the values that can be expected on the system, as the transients arising from the initiation of the fault are not included. The results of the a-c calculating board study are probably an upper limit as

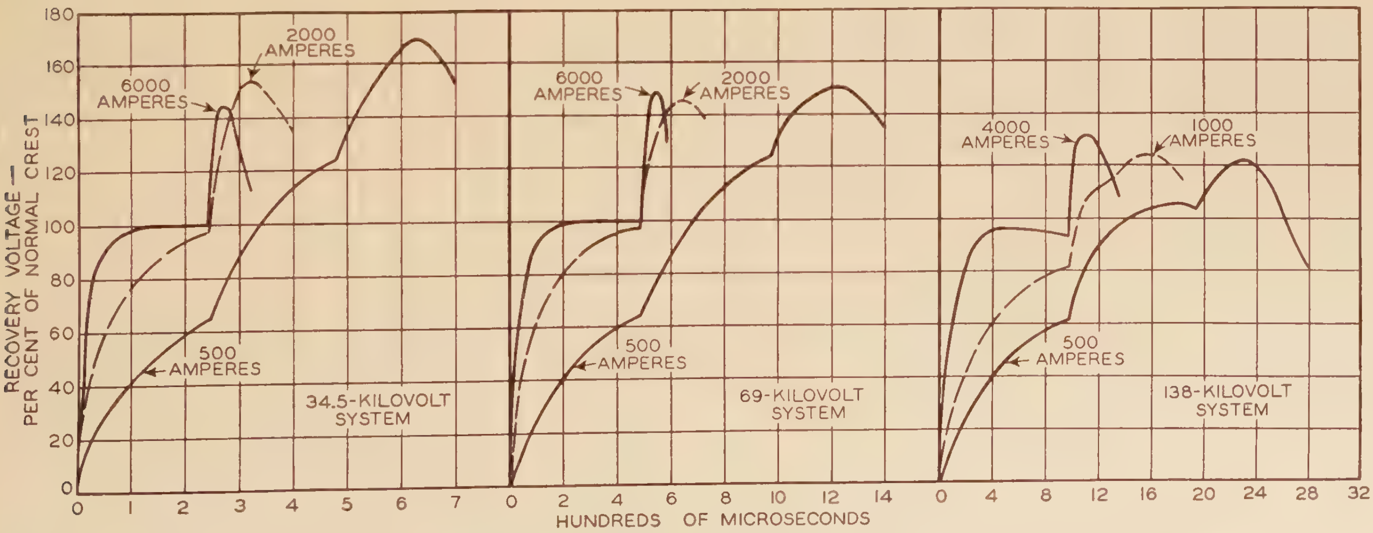

Figure 11. Calculated recovery voltages for single line-to-ground fault on solidly grounded systems

these include the effect of initiating transients and some extraneous oscillations introduced by the networks. The actual determining conditions are probably between these two limits but the relative position has not been definitely determined as it is not of immediate interest in presenting broadly the results of this series of studies.

It is of interest to note the effect on the first crest of varying the length and number of lines, as previously was done in connection with the effect on the second crest in discussing figure 10. For example, if four lines of the same length were used for, say, the 2,000-ampere case the recovery-voltage curve would approximate that of the 500-ampere case, since one may assume four fictitious systems supplying 500-ampere symmetrical short-circuit currents operating in parallel to give the 2,000 amperes.

Part II

Application of the Data

It is the purpose of this section to show broadly how the recovery-voltage data can be used in the application of apparatus to a system. Although the recovery-voltage data presented is useful in a large number of applications, the particular application of the deion protector tube will be taken as an illustration. The case of the 34.5-kv solidly grounded system with 22.5 miles of transmission line with a symmetrical three-phase short-circuit current of 2,000 amperes at the sending end has been selected. These data are plotted in the form of recovery-voltage magnitude-time curves as illustrated in figure 12. The points joined with broken lines are for the first crest and maximum overshoot taken from the general curves of figures 6 and 7. The particular fault and arc resistance condition is identified by the notation on the figure. In figure 12 there is also plotted the calculated curve taken from figure 11. There are also plotted curves P_1, P_2, and P_3, which are the insulation recovery-strength curves for three different deion protector tubes with different inner bores but the same fiber length. An examination of the curves of figure 12 shows that there are certain conditions for the solidly grounded system that would result in higher recovery-voltage characteristics on the system than the protector tube could provide in insulation recovery strength. More specifically, points $A2$ and $B2$ for first crest are definitely above the insulation-recovery curve P_3 whereas all of the points for the solidly grounded system are definitely below the insulation recovery-strength curves for both protector tubes P_1 and P_2. As previously discussed in connection with figure 11, if there are parallel lines the first crest is decreased in magnitude for a given time or for a given magnitude the time is increased, making the first crest less significant. For the case just considered, if two parallel lines were used protector tube P_3 would be entirely satisfactory.

The effect of reactance grounding is also of interest and this is illustrated in figure 12 by plotting the more significant conditions from figure 7. A comparison of the data from figures 7 and 12 shows for the single line-to-ground fault, that the interruption problem diminishes as the neutral reactance is increased. It will further be noted for the double line-to-ground faults with the higher value of reactance that the severity is increased very materially over that of the solidly grounded system to a point that it approaches protector tube P_2.

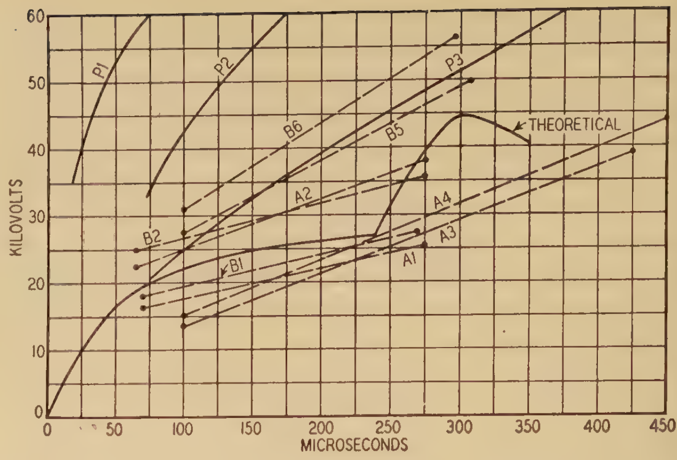

Figure 12. Comparison of system recovery voltage and insulation recovery strength for deion protector tubes for 34.5-kv solidly grounded system supplying 2,000 amperes three-phase short-circuit current at sending end

P_1, P_2, P_3—Insulation recovery strength for deion protector tubes of identical design except for increased bore for higher subnumerals

B6, B5, etc.—System-recovery voltage

Nomenclature: *A*—Single line-to-ground fault
B—Double line-to-ground fault
1—Solidly grounded system, arc resistance
2—Solidly grounded system, no arc resistance
3—Low-reactance grounded system, arc resistance
4—Low-reactance grounded system, no arc resistance
5—High-reactance grounded system, arc resistance
6—High-reactance grounded system, no arc resistance

Correlation of System Recovery Data and Operating Experience With Deion Protector Tubes

It is of interest to compare the conclusions drawn from figure 12 with experience from an actual system. Protector P_1 has been applied to a particular system having an aggregate of 22 miles of line in three circuits and a symmetrical three-phase short-circuit current nearly the same as that of figure 12. The fact that there are three circuits will decrease the first crest but otherwise it should be similar to figure 12. Experience has been entirely satisfactory as would be concluded from an examination of these curves.

Protector tube P_1 has been applied to another system having an aggregate of 12 miles of line in three circuits and with a symmetrical three-phase short-circuit current of approximately three times that of the system used for figure 12. The fact that there are three circuits will again decrease the magnitude of the first crest. The magnitude of the maximum will remain practically the same but the time to maximum will be decreased from 275 to 115 microseconds. This is because, as previously shown, the time varies as $\sqrt{LC}$. L varies inversely as the short-circuit current and C varies directly with the aggregate line length. The line length is decreased in the ratio of 12 to 22.5 which will decrease the time as the square root of this ratio or to 73 per cent; also the fact that the source inductance has decreased to one-third will decrease the time 58 per cent, making a total reduction of 42 per cent. Experience has again been entirely satisfactory as would be concluded from an examination of the curves of figure 12.

In the case of protector tubes P_1, P_2, and P_3, shown on figure 12, the designs are identical except the bore is increased for the higher subnumerals. It will be noted that the insulation recovery characteristics of the protector tube are lower as the bore increases. In the normal operation of the deion flashover protector tube successive operations tend to increase the bore. It has been recognized in the application that after a number of operations the bore will eventually erode to a diameter that will cause the protector to fail. This is illustrated by a comparison of curves P_1, P_2, and P_3. For example, if protector tube P_1 leaves the factory with a definite inner bore it is quite conceivable that after a number of operations the bore will increase to approach the characteristics of protector tube P_2 or even protector tube P_3. It is, therefore, seen that eventually the protector will fail to clear.

It is believed that there has been undue apprehension in connection with the erosion of the protector tube for the practical application. Through the co-operation of the Interstate Power Company it has been possible to secure direct measurements of this factor on the oldest extensive application of protector tubes. This experience was obtained on the 66-kv line joining Dubuque and Clinton, which consists of 47 miles of single-circuit line with flat configuration and seven miles of double-circuit line with vertical configuration. Ground wires are not used and the line is insulated with four ten-inch units, spaced five and three-fourths inches. The line was placed in service August 15, 1926, and in six years time, before the deion protector tubes were installed, there were 277 interruptions that could be traced to lightning. This is an average of 46 interruptions per year. The large number of outages per year is direct evidence that there were and are a large number of strokes to the line per year.

Deion flashover protector tubes were installed on this line in August 1932. The following is an interruption record after the installation was made:

Period	Interruptions
August 1932 to December 1, 1932	0
Year 1933	3
Year 1934	0
Year 1935	3
Year 1936	8
January 1, 1937 to August 20, 1937	2
Total	16

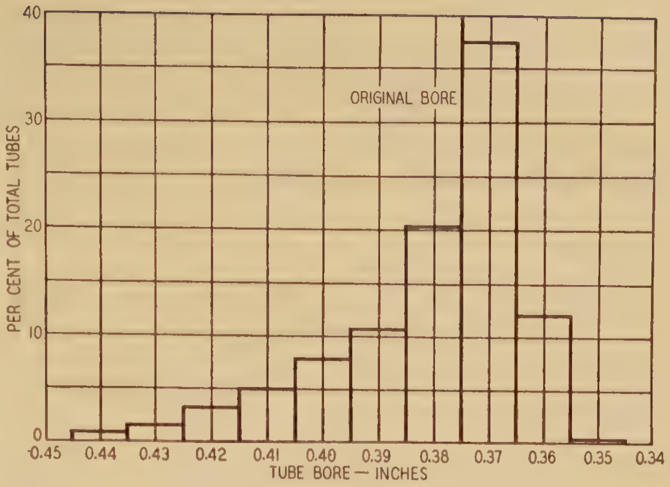

Figure 13. Erosion data obtained after five years' operation of deion protector tubes installed on the Clinton-Dubuque line of Interstate Power Company

This is an average of 3.1 interruptions per year which corresponds to a reduction of 15 to 1. An analysis of these explained 15 of the 16 interruptions. In the year 1933 two protector tubes were destroyed due to high surge current estimated at from 75,000 to 100,000 amperes. In the latter part of 1935 and the early part of 1936 there was a sudden increase in the number of outages which led to an investigation. The outstanding improvement in the performance of the lines justified at times shutting down the station at Clinton although the original application assumed it in operation. This change resulted in reducing short-circuit current at the Clinton end of the line to approximately one-third of the minimum rating of the deion flashover protector. An analysis of the outages for 1935, 1936, and 1937 indicated that all these failures occurred within a few miles of the city of Clinton. An analysis of this particular condition indicates that with the lower short-circuit currents the recovery-voltage strength of the protector tube is lower than the recovery voltage on the system with the result that the protector tubes failed to clear. In August 1937 the protector tubes on the Clinton end covering a distance of approximately 20 miles, were replaced with protector tubes having higher insulation recovery strength. No outages have since resulted on this line up to the time of writing although there have been a number of lightning storms in the vicinity of the line.

In changing the protector tubes a program was carried out by the Interstate Power Company whereby it was possible to obtain bore measurements on all of the protector tubes originally installed. This allows a detailed analysis of the increase of bore or the decrease of insulation-recovery strength as a result of a large number of operations in five years. A limit of 0.45 inches was set for the bore that would be satisfactory for the original application. The original bore of the protector tubes was 0.375 inches and they were very close to this when they left the factory. Figure 13 shows the range of bores after the five years of operation, these being given to the nearest one-hundredth of an inch. It is of interest that none of the protector tubes have reached the limit set as satisfactory for the original application. Only 2.7 per cent have reached 0.43 inches and five per cent have reached 0.42 inches. The protector tubes that were eroded the most were installed at high points on the line. The fact that some protector tubes are below the 0.375 inch is explained by the fact that fiber will swell and the protector tubes with 0.375 inch bore or less have swelled more than they have been eroded by operation. The probability is that the protector tubes below this bore diameter have had few, if any, operations.

Summary

1. This paper presents a general picture of the recovery-voltage characteristics of transmission systems obtained from the study of nine selected systems subjected to the varying factors encountered in practical operation. The a-c calculating-board method has been of major importance in carrying out this investigation.

2. The recovery-voltage characteristics of systems subjected to faults which are cleared without a line-sectionalizing operation are much less severe than that for the clearing of the last circuit breaker on a bus. This difference is so marked that advantage should be taken of it, in the design of certain pieces of apparatus.

3. The method of analysis and the data presented should be of value in the application of certain pieces of apparatus and in the preparation of test codes for specific devices.

4. This general analysis is of immediate interest in connection with the application of protector tubes, and operating experience with this device supports the analysis. Erosion of the protector tubes due to operation is such that the insulation-recovery characteristics are not changed at an impractical rate.

Acknowledgments

The authors wish to acknowledge the co-operation of Messrs. W. Wisco and H. Chambers of the Interstate Power Company in securing the valuable data on the performance of the protector tubes on their system. They also wish to acknowledge the helpful suggestions of their associates, particularly Mr. R. L. Witzke who conducted the a-c calculating-board studies and prepared the data presented.

References

1. System Recovery Voltage Determination by Analytical and A-C Calculating Board Methods, **R. D. Evans** and **A. C. Monteith.** Electrical Engineering, June 1937, volume 56, page 695.

2. Breaker Performance Studied by Cathode Ray Oscillograms, **R. C. Van Sickle.** Electrical Engineering, volume 54, page 178.

3. Travelling Waves on Transmission Systems, **L. V. Bewley** (a book). John Wiley and Sons, New York, 1933.

Discussion

W. J. Rudge, Jr. (General Electric Company, Pittsfield, Mass.): Messrs. Evans and Monteith have made a valuable contribution in their paper on the recovery-voltage characteristics of transmission systems. Since their studies were conducted on an a-c calculating board, it will be of considerable interest to compare the results given in their paper with results which were obtained by actual measurements in staged field tests.

In figure 8 a plot is given of recovery voltage crest in per cent of normal line-to-neutral voltage. The recovery voltage is given for both solidly grounded neutral systems and systems grounded through reactors. This curve indicates that on solidly grounded neutral 115-kv system the recovery voltage will rise to about 150 per cent of normal. We have recently completed tests on a 115-kv system where the recovery voltage measurements varied from 115 to 178 per cent of normal. We have also made tests on a 26.4-kv system which was grounded through resistance where the recovery voltage measured to ground varied between 115 and 187 per cent of normal. Similar tests on a 33-kv system with neutral grounded through resistance give recovery voltages varying between 100 per cent and 185 per cent of normal. Tests made on a 33-kv isolated neutral system give values ranging between 100 and 170 per cent of normal.

Referring to figure 11 of the Monteith-Evans paper, it may be noted that the highest values of recovery voltage occur with the lower currents on the low-voltage system and on the higher-voltage system the highest recovery voltage occurred with the larger currents.

Referring again to our actual field tests, the data on each of the four separate field tests mentioned above indicates that the highest recovery voltage occurs with the lower values of short-circuit current. Further data may, however, show that it is possible to obtain as high recovery voltage with large currents as have been obtained with the lower values. In the field tests the highest values of recovery voltage occurred with currents ranging between 500 and 1,500 amperes whereas the lower values of recovery voltage were for currents in the order of 3,000 amperes.

In giving these results, we do not intend to infer that low values of recovery voltage do not occur with low values of current, as there are many instances where the recovery voltage varied between 100 per cent and 150 per cent of normal in the low range of short-circuit currents. The data from field tests cited above show the highest values of recovery voltage occurring in the range of currents obtained.

In other words, this comparison of field data with the data obtained on the a-c calculating board, show that the results obtained from the board can be no more accurate than the basic data upon which the board is set up. It is therefore essential to have an adequate background of field tests before accurate results can be expected from the a-c board.

On the basis of the field tests, it appears that the crest recovery-voltage characteristic, when plotted against system voltage, is almost a flat line, whereas in figure 8 of the Monteith paper, the curve indicates that for the higher system voltages the maximum recovery voltage has a downward trend.

We note in figure 12 of the Evans-Monteith paper that the characteristics for the protector tubes *P*-1, *P*-2, and *P*-3 do not extend to the region near normal voltage so that when comparing the recovery characteristic of the system with recovery characteristic of the tube, one would infer that the rate at which the voltage rises at the early part of the curve has no effect on tube operation unless the voltage rose at least to the point where the tube characteristic curves begin. We would like to have the authors explain whether these curves are the limit of the data which has been taken on the tube, or whether we have correctly interpreted their results. Tests which we have made on tubes indicate that it is essential for the characteristic curve to be extended back to voltage equal to or even less than normal, as tubes may fail to clear because of too rapid rate of voltage rise, rather than long time in which the peak value of the circuit recovery voltage occurs.

R. C. Van Sickle (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Although the data presented in this paper applies specifically to protector-tube application, it has additional interest to those associated with high-voltage circuit breakers and their application, as is suggested by the authors. The recovery-voltage characteristics of the typical circuits on which breakers are applied cover a wider range and unfortunately the upper limit is not as well fixed as in the case of flashover protectors because the minimum amount of effective capacitance is more difficult to determine. That the effects of lines and loads greatly reduce the severity of the voltage recovery characteristics has already been demonstrated by measurements taken during field tests on circuit breakers but such data are naturally limited and apply to the particular conditions existing for the test. Consequently, the data presented in this paper is a welcome addition to the general fund of information on the severity of some of the service conditions which may be imposed on circuit breakers.

The characteristics imposed on a tube at the far end of a line are the same as those on a breaker opening at the end of the line. Likewise, the characteristics imposed on a tube at the near end of a line are the same as the characteristics imposed on a circuit breaker opening one line with another line still connected to the same bus.

Since the lengths of the lines have been chosen as short as are typical for the corresponding voltage, the effects produced can be regarded as being the minimum which would normally be expected. A 138-kv circuit having a three-phase short-circuit current of 500 amperes might impose, on the circuit breaker during a single line-to-ground fault, a voltage crest of 190 per cent which occurs about 110 microseconds after current zero. This corresponds to a voltage-recovery rate of 1,020 volts per microsecond. The data in this paper shows that a parallel line would reduce the maximum voltage from 190 per cent to 135 per cent and the rate from 1,020 to 104 volts per microsecond.

Other data shows that locating the circuit breaker at a substation fed by a 90-mile 138-kv line with the neutral solidly grounded and a three-phase short-circuit current of 826 amperes, subjects it to a maximum voltage 160 per cent of normal and a voltage-recovery rate of 89 volts per microsecond. These conditions are approximately the same as those encountered with a parallel line.

These are only a few of the interesting comparisons which can be made by use of the data presented in this paper.

D. C. Prince (General Electric Company, Philadelphia, Pa.): This paper naturally divides itself into two parts; (1) methods of analysis of circuits to obtain the form of recovery-voltage characteristics; (2) the nature of the interrupting characteristics of the expulsion tube with reference to recovery voltages impressed upon it.

There are several methods already in use for determining recovery voltage, ranging all the way from straight calculation through the calculating board methods, discussed by these authors, and ending up at the other extreme with field tests by cathode ray oscillographs. With the addition of the authors to this situation there are available methods of determining recovery voltage forms for practically all conditions.

The second half of the paper is outstanding in that it represents the most exact correlation yet established between any circuit interrupting apparatus and the recovery voltage of the circuit upon which it must work. In the body of the paper, it is stated that the important elements of recovery voltage are the length of time to reach the crest value and the magnitude of that crest value. This statement is not supported by the test information shown. Referring to figure 12, it appears that the variation of strength with time for three expulsion tubes is shown in the curves P_1, P_2, and P_3. If the recovery voltage lies wholly below any one of these three curves, the corresponding design of expulsion tube may be expected to operate satisfactorily.

If, on the other hand, there is a point where a curve of recovery voltage crosses one of these lines P_1, P_2, or P_3, as the case may be, at that point the tube will break down. It would be interesting to know how these curves P_1, P_2, and P_3, were obtained since if this statement of the case is correct, this represents the most accurate correlation between the behavior of any circuit interrupting device and the recovery voltage characteristics of a system yet published.

Above and below the portions plotted in figure 12, it is presumed that waves likely to be obtained would not cross the portions of these lines not plotted, but this could be judged with considerably more assurance if the lines were extended particularly in the direction of shorter times.

C. N. Weygandt (University of Pennsylvania, Philadelphia): I note that in the method used by the authors an elaborate switching scheme for the cathode ray oscilloscope is required in order to record the high-frequency transients, and also that when the capacitance of the actual circuit is low capacitance of leads and so forth becomes a source of trouble. I should like to suggest an equivalent circuit which may in some cases avoid these difficulties. Suppose that the circuit of figure 1 is to be studied.

The voltage across the switch s can be obtained as the time function corresponding to the operational expression:

$$e_v(t) = \frac{E}{L}\frac{p\omega}{p^2+\omega^2} \times \frac{1}{pC + \frac{1}{R_c} + \frac{1}{R_L + pL}}$$

Let us construct an equivalent circuit such that its operational impedance is the reciprocal of that of the original circuit. The inductance now has a value numerically equal to the capacitance in the original circuit and the capacitance is equal to the original value of inductance and the resistances are reciprocals of their original values. The current which flows when the switch is closed at the instant $t = 0$ is:

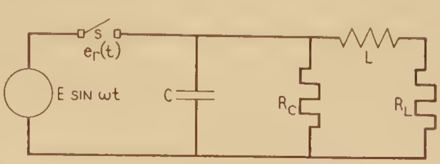

Figure 1. Original circuit

$$i(t) = \frac{E}{L}\frac{p\omega}{p^2+\omega^2} \times \frac{1}{pC + \frac{1}{R_c} + \frac{1}{R_L + pL}}$$

which is identical with the voltage across the switch in the first circuit. Moreover by reducing the frequency of the applied voltages and consistently altering the values of the parameters, the natural frequency may be reduced so that it may be recorded with an ordinary magnetic oscillograph. Also since the applied voltage in the equivalent circuit represents the interrupted current in the actual circuit it should be more easily possible to simulate interruption when the current is not zero, nonlinear arc characteristics and the like. A numerical example follows:

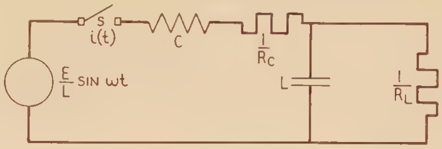

Figure 2. Equivalent circuit

Given an original circuit with the constants in the left-hand column, the equivalent circuit will have the constants in the right-hand column:

Original Circuit			Equivalent Circuit		
0.25	millihenry	$= L$	25	microfarads	$= L$
0.00025	microfarad	$= C$	2.5	millihenrys	$= C$
0.01	ohm	$= R_L$	10^6	ohms	$= 1/R_L$
10^b	ohms	$= R_c$	0.01	ohm	$= 1/R_c$
377	per second	$= \omega$	0.377	per second	$= \omega$
4×10^6	per second	$= \frac{1}{\sqrt{LC}}$	4,000	per second	$= \frac{1}{\sqrt{LC}}$
60	cycles per second	$= f$	0.06	cycle per second	$= f$

C. Concordia (General Electric Company, Schenectady, N. Y.): In the past few years there has been a large number of papers written on recovery voltage. One of the striking features of these papers is that there are apparently two different viewpoints about the relative importance of the various factors involved in recovery voltage calculations. One group leaves us with the impression that the important factors are the traveling waves and their reflections, the other that the important factors are the natural frequencies of the circuit. The present paper by Messrs. Evans and Monteith appears to fall in the latter class.

There need be no essential or theoretical conflict between the two points of view. On the other hand, as the traveling waves depend on the surge impedances and transmission distances, while the natural frequencies depend in practice on lumped circuit approximations to the actual system, one may arrive at different conclusions regarding a particular system by the two methods of approach. It is essential to examine carefully each case to determine what must be considered and what can safely be neglected.

One may construct a lumped circuit which possesses the same first, second, etc., natural frequencies and the same steady state characteristics as the actual circuit. In a practical case one will match the circuit frequency response characteristics only up to some limiting frequency. The initial response of such a circuit to an impulse will bear no relation to the initial response of the system.

Similarly one may determine the surge impedances of the system and from them calculate the correct initial response to an impulse. However, consideration only of the surge impedances and reflection times will not result in a correct determination of the oscillations of the recovery voltage.

It is evident therefore that in the general case both effects must be taken properly into account. In some cases, however, the reflection times are so short that the circuit behaves very nearly like its lumped circuit equivalent. In other cases the reflection times are sufficiently great so that the voltage during the period of interest may be determined entirely from the surge impedances. Still more significant is the fact that for some applications the initial response (e.g., the initial rate of use of voltage) is the most important factor, while for other applications the magnitude of the voltage swing may be the most important. In the general case again the entire recovery characteristic must be considered.

L. G. Smith (Consolidated Gas, Electric Light, and Power Company of Baltimore, Baltimore, Md.): Data of the type included in this paper are of real interest to those companies applying deion protector tubes and expulsion protective gaps. Our company has made several applications of these tubes on our 13.2-kv lines and a few isolated applications at 110 kv. Details of these installations are covered in a discussion on page 1509 of the 1937 AIEE TRANSACTIONS.

One of the problems in protector-tube applications is to obtain tubes with a range of current interrupting capacities, within which range the currents actually encountered in the particular application will lie. It is recognized that all expulsion devices have two limits on their current interrupting capacity:

1. The maximum current, which is limited by the bursting strength of the tube notwithstanding the pressure produced by the high currents.

2. The minimum current below which sufficient pressure is not developed to extinguish the arc.

It is understood that the minimum current rating of an expulsion device depends to a large extent upon the rate of rise of recovery voltage. For a given bore diameter the lower the rise of recovery voltage the lower the minimum current that can be interrupted.

Since protector tubes are applied by connecting them from each phase to ground, the ground connection usually being a common connection for all three phase tubes the maximum current interrupting capacity must be sufficient to clear a phase-to-phase fault if two tubes are discharging simultaneously. On the other hand, the minimum interrupting capacity of the tube is determined by the maximum ground resistance, if a single tube discharges. As ground resistances may at times be high and also vary over considerable ranges of values due to weather conditions, it is frequently necessary to use a so-called multiplex installation in which phase tubes of high current interrupting capacity are installed in each phase and a single ground tube installed in the common ground connection, this tube having a lower current rating. If more definite information were available concerning the probable rates of rise of recovery voltages on various systems it should be possible to extend the application of tubes and possibly eliminate the multiplex connection in many instances. Therefore, information on this point is desired by the industry.

R. D. Evans and A. C. Monteith: The principal objects of our paper are to provide (1) a general picture of the recovery-voltage characteristics of transmission systems which has been obtained with the aid of the a-c calculating board and (2) to illustrate the use of the recovery-voltage data in connection with the application of a specific arc-interrupting device, the protector tube. This is the first time that a broad picture of the recovery-voltage problem on transmission systems has been presented. Until such a picture is available and generally understood, refinement in methods of analysis and greater detail in the characteristics of the device are of secondary consideration. A review of the discussions shows a general agreement with the importance of our objectives and the interpretation of the data presented. This general viewpoint should be kept in the mind in considering the replies to the specific discussions.

We fully agree with Mr. Concordia that there is no essential or theoretical conflict between recovery-voltage calculations by traveling waves and by networks with lumped constants, provided the network constants have been suitably chosen and provided that both types of calculation have been carried to a fair degree of refinement. Both methods have been discussed and used in the paper, one method providing a check against the other. It is the particular advantage of the method using networks with lumped constants that makes possible the use of the a-c calculating-board method which provides a practical form of solution for general analyses, the results of one such study being presented in the paper under discussion. This point of view was discussed in greater detail in our paper entitled "System Recovery Voltage Determination by Analytical and A-C Calculating-Board Methods" presented at the 1937 summer convention in Milwaukee.

Mr. Van Sickle's discussion is of value in that it shows the application of the system recovery voltage data to another specific apparatus problem, the circuit-breaker problem.

Mr. Rudge has presented certain results of field tests and made comparison of measured voltage magnitudes with those of figure 8 of the paper. In this connection it is pertinent to observe that the recovery voltages of figure 8 are definitely associated with the figures 6 and 7 which incorporate time as well as magnitude. In figure 5 we have shown that higher recovery voltages than those plotted in figures 6, 7, and 8 can appear on the system but those voltages were generally associated with considerably longer time so that they were not considered as significant as the voltages plotted. It is, therefore, unfortunate that Mr. Rudge has not given the times associated with the voltage magnitudes presented in his discussion so that a detailed comparison could be made. Mr. Rudge's discussion raises the question as to whether more severe conditions are met in the field than are indicated in the paper. This question cannot be answered unless the times associated with the recovery voltage magnitudes are also presented. Results of tests given in the previous paper just referred to, together with the results of other tests, give recovery voltage magnitudes and times checking closely with the values given in the paper under discussion when these are put on a comparable basis.

Mr. Rudge also makes comparisons between the results of field tests and the data presented in the paper with respect to maximum recovery voltage as a function of fault current and as a function of system voltage. Again the comparisons are not complete unless time as well as magnitude is considered.

In the discussion Mr. Rudge implies, but does not state, that the systems tested fall within the range of systems studied on the a-c calculating board. It would be valuable if more detailed information had been given on the systems tested so that direct comparisons could be made.

Concerning field tests, we have recognized and have emphasized in both of our papers the desirability and necessity of such tests as a means for providing benchmarks. We do feel, however, that, on account of the limitations in making such tests, it is difficult if not impossible by this means alone to obtain a broad grasp of the recovery voltage problem.

Both Mr. Rudge and Mr. Prince have raised the question of the characteristics of protector tubes in the short time range. The object of figure 12 is not to provide a complete picture of the characteristics of protector tubes but instead to illustrate the use of the recovery voltage data given in the paper in connection with the application of a particular piece of apparatus, the protector tube, giving only the characteristics of tubes essential for this purpose. We quite agree with Mr. Rudge's statement that protector tubes may fail to clear at voltages less than normal crest value which have a "too rapid rate of voltage rise." The operation of a protector tube depends on the tube design and on the characteristics of the circuit. For example, tube *P*-3 would fail at less than normal crest for the particular system considered in figure 12, but tube *P*-1 would obviously give satisfactory operation for the same system recovery voltages. More data is available on the characteristics of protector tubes but this is not believed to be pertinent to the present discussion.

Mr. Prince seems to have misinterpreted our discussion on the application of the data in that he infers that we believe the pertinent point in the recovery-voltage problem is the maximum voltage crest and corresponding time. The basic factor to be considered is the relation of the complete curve of system recovery voltage and the complete curve of insulation recovery voltage. However, the complete curve is rarely needed and usually the conditions may be defined by a few critical points usually describable as first crest and maximum crest. We wish to emphasize the fact that these critical points must be given in terms of voltage magnitude and time, or some pair of related quantities, and cannot be given in terms of a single quantity such as the rate of rise of recovery voltage.

Mr. Prince inquired as to the method of obtaining insulation recovery curve of the protector tubes of figure 12. The points were obtained by measuring the voltage and time on cathode-ray oscillograms when restriking occurred. Therefore, as stated by Mr. Prince, if the system recovery voltage curve crosses the insulation recovery curve, failure will occur at the point of crossing.

Mr. Weygandt has made an interesting suggestion to replace the equivalent network used in recovery voltage studies by a "reciprocal" network in order to avoid the effects of stray capacitance. This is not, however, an important limitation of the a-c calculating-board method. This is due to the fact that it is usually possible to select an equivalent network using high values of capacitance and still obtain the desired natural frequencies. An alternative method is to use different ratios of fundamental to natural frequencies as explained in the closing discussion of our previous paper (see ELECTRICAL ENGINEERING, October 1937, page 1311). It is also important to retain the advantages inherent with the present procedure which permits obtaining in a straightforward manner the transient effects due to the application of a fault and its clearing as well as the effects of subsequent restrikes.

We agree with Mr. L. G. Smith that when a broad knowledge of the characteristics of recovery voltages of systems is obtained and when more data on the performance of protector tubes becomes available, a more scientific application of protector tubes will become possible and this in turn will eventually lead to a simplification of the application procedure.

Critical Conditions in Ferroresonance

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Introduction

THE APPLICATION of "ferroresonant" circuits to engineering problems has become increasingly important from both theoretical and practical considerations. While much progress has been made in the general study of ferroresonance, treatment is lacking in an accurate description of, perhaps, the most interesting part of the phenomena, namely, the so-called critical points at which the current suddenly changes in value. From a practical viewpoint, it is this characteristic property that makes ferroresonant circuits useful as sensitive elements in relay and control apparatus. Accordingly, there is a definite need for simple quantitative information that completely predetermines the behavior of the circuit under critical conditions and specifies the required circuit parameters in terms of known quantities.

Of the various methods employed in the study of ferroresonance, the method of graphical solutions presents itself as the most flexible and gives a somewhat better physical picture of the phenomena. On the basis of this method, a simple rule is proposed for the criteria of stability which uniquely determines the critical conditions and permits analytic development of simple formulas defining the critical quantities. An interpretation and discussion of equations bring to light several interesting aspects of the phenomena and point to inaccuracies of previous methods. Various applications of the theory are given.

Review

The ferroresonant circuit consists of elements of resistance and capacitance connected in series with an iron-core inductance. In the study of ferroresonant circuits with a-c applied voltage, rigorous mathematical treatment has been found practically impossible. With certain simplifying assumptions, however, solutions[3,7] have been given which serve in a general sense to describe the nature of the phenomena. Essentially, the methods followed in treating the series circuit (figure 1) require the determination of a functional relationship between the current and the inductance of the iron-core reactor. Under the assumption of sinusoidal variation of current, a continuous voltage characteristic is obtained from the well-known circuit equation,

$$E = I\sqrt{R^2+\left(\omega L-\frac{1}{\omega C}\right)^2}\ ,\ L=\Phi(I) \qquad (1)$$

Several theoretical characteristics are given in figure 2 showing the influence of resistance and capacitance. To attach meaning to the multivalued curves thus obtained, the region in which the voltage decreases with increase of current is designated as unstable since it is physically unattainable. At the extremities of this region therefore, an abrupt change in current takes place as indicated by the dotted lines. The points of sudden transition of current are defined as critical points (1, 2).

It is of particular interest to note that the analytical method provides no means for determining the critical points except by the graphical procedure just outlined. Furthermore, it would appear that the critical points (2) associated with the collapse of current are bounded by the resistance line (IR) since the variable impedance has a minimum value equal to the resistance. This relation, however, is at most approximate and does not hold in general.

The method of graphical analysis, first introduced by Stark,[4] is advantageous because of its simplicity. In this representation, the volt-ampere characteristics of the reactor ($E_L = f(I)$) and the condenser ($E_C = I/(\omega C)$) are employed to determine graphically the variation of the resultant reactive voltage which is given by the difference of ordinates (figure 3). The results are then applied to a modified form of equation 1,

$$E = \sqrt{(IR)^2+\left(E_L-\frac{I}{\omega C}\right)^2} \qquad (2)$$

and operating characteristics similar to those in figure 2 are obtained.

A refinement of this method, due to Rouelle,[19] requires the separation of the reactor voltage into active and reactive components on the basis of fundamental frequency. A predetermination of the operating characteristics shows good agreement with experimental results; but just as in the previous case, the critical points are not defined.

Method of Graphical Solutions

Historically, the method of graphical solutions represents one of the earliest attempts to explain the multivalued character of ferroresonance and was introduced by Bethenod[1] in a brief treatment on the ideal circuit. The method was later extended to the general circuit by Margand[6] whose interpretation uncovered several important facts, particularly concerning stability. There remain, however, a few considerations that need amplification in order to arrive at a better understanding of the critical conditions.

The graphical solution for the series ferroresonant circuit (figure 1) follows from two independent relations for

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1. For all numbered references, see list at end of paper.

reactor voltage; namely, the volt-ampere characteristic of the reactor,

$$E_L = f(I) \tag{3}$$

and the circuit equation (assuming sinusoidal quantities)

$$E_L = \pm \sqrt{E^2 - (IR)^2} + \frac{I}{\omega C} \tag{4}$$

In the right-hand member of equation 4, the expression under the radical represents an ellipse whose principal axes have values E and E/R, respectively. The second term is a straight line through the origin having a slope

$$\tan \gamma = \frac{1}{\omega C} \tag{5}$$

The sum of the two terms is an ellipse (a fact that may be readily ascertained) whose intersections with the reactor characteristic are the graphical solutions for current (points 1, 2, and 3 in figure 3). The representation in this form because of its component nature permits a simple graphical study of the circuit characteristics with a variation of any of the parameters. To avoid ambiguity of multiple current values, however, it is necessary to distinguish the real or stable solutions from the unstable solutions.

Stability of Current Values

In the previous methods outlined, the question of stability of certain current values arose as a result of the current-voltage relations obtained theoretically. The portion of the curve that was found experimentally nonexistent was classified as unstable, and the curves were modified accordingly to account for the characteristic discontinuity (dotted lines in figure 2). The method of graphical solutions, on the other hand, provides a means to test the stability of the individual solutions and gives, therefore, a better physical picture of the related phenomena.

It was not until Margand's treatment appeared that a reasonable explanation was given concerning the stability of the various points. He showed that points 1 and 2 (figure 3) represented stable solutions, whereas point 3 represented an unstable solution. The following reasons are the basis for this distinction.

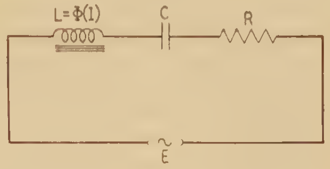
Suppose that to leave a stable point, the current suddenly changes by an amount ΔI. The effect of this change upon the circuit may be studied from the relation,

$$(RI)^2 = E^2 - \left[f(I) - \frac{I}{\omega C} \right]^2 \tag{6}$$

If the quantity $[f(I) - I/\omega C]$ increases in magnitude with a slight increase of current, then $(RI)^2$ tends to decrease in accordance with equation 6. The sense of variation of $(RI)^2$, however, is opposed to the assumed change of current; therefore, the point is indicative of a circuit condition in favor of stability. If on the contrary $[f(I) - I/\omega C]$ decreases in magnitude with increase of current, $(RI)^2$ tends to increase, indicating a sense of variation similar to that of the current. Under this condition, the current continues to increase, and the point is characterized as unstable. In a corresponding manner, the same argument could be advanced if the current were assumed to decrease slightly.

The stability of the various points may be established by observing graphically the variation in magnitude of the quantity $[f(I) - I/\omega C]$ as shown by the hatched ordinates in figure 3. Thus, point 3 corresponds to an unstable solution since $[f(I) - I/\omega C]$ decreases with increase of current. The opposite is true for points 1 and 2, hence these are stable solutions.

Figure 1. Ferroresonant circuit



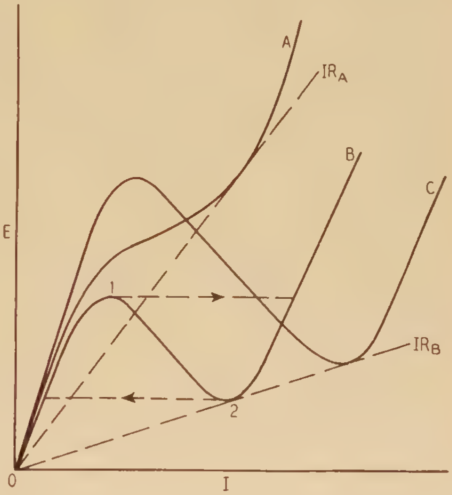


Figure 2. Voltage as a function of current

While the foregoing principle permits a distinction between stable and unstable current values, there appears to be an inconsistency concerning the limiting conditions. For example, take the case where capacitance is the only variable parameter and observe graphically the conditions for the limit of stability. At point 1 the limit of stability takes place when the reactor characteristic and the ellipse are tangent to each other, but at point 2, it occurs when the condenser line $(I/\omega C)$ intersects the reactor characteristic at the maximum value of current, E/R (figure 4). Consequently, with further increase of capacitance, point 2′ which defines a current value less than E/R should be unstable according to the above principle of stability. This, however, is contrary to experience, since it has been observed that the current may decrease considerably beyond the maximum value before instability occurs (see figure 15). Margand's explanation does not account for this effect since it is based upon the aggregate effect of the squared quantities in equation 6, thus concealing a change of sign. More specifically, the criteria for stability should be based upon the points of intersection of the two curves in such a manner that each portion of the ellipse as divided by the condenser line is properly expressed with respect to sign. As a modification, therefore, the following rule is proposed.

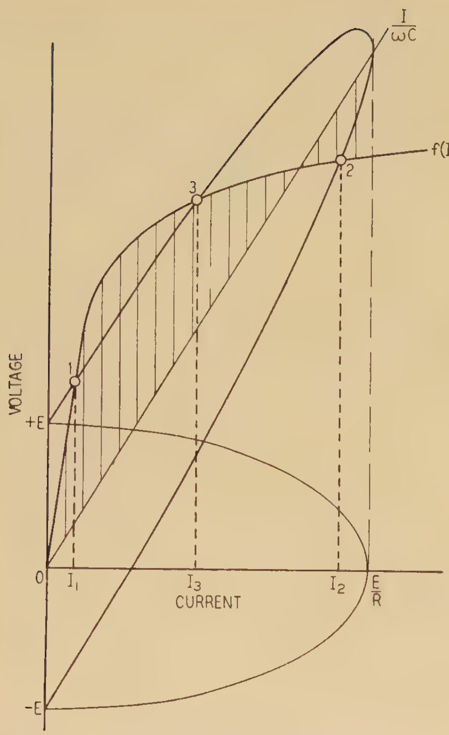


Figure 3. Graphical solutions of ferroresonant circuit

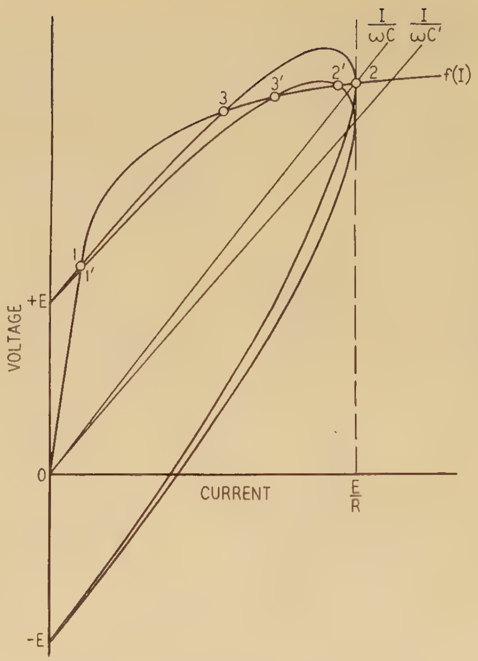


Figure 4. Influence of variation of capacity upon stability; C′ > C

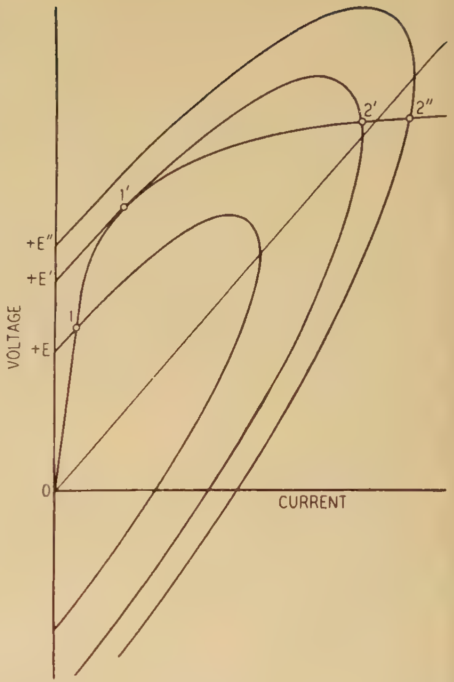


Figure 5. Graphical method of obtaining circuit characteristic, current as a function of voltage

With respect to intersections of the reactor characteristic and the upper part of the ellipse, the graphical solution is given by

$$f(I) = +\sqrt{E^2 - (IR)^2} + \frac{I}{\omega C} \tag{7}$$

Any such point is stable if, for a slight change in current, $f(I)$ correspondingly changes at a greater rate than the right hand member of (7), taking cognizance of the sense of variation of current. Thus, for an increment of current, the ordinate of the reactor characteristic must be greater than that of the upper part of the ellipse, and less, if the current is assumed to decrease slightly.

For intersections associated with the lower part of the ellipse, the graphical solution is given by

$$f(I) = -\sqrt{E^2 - (IR)^2} + \frac{I}{\omega C} \tag{8}$$

and the conditions for stability are reversed. In this case a point is stable if the right hand member of (8) changes at a greater rate than $f(I)$ corresponding to an assumed deviation of current.

An application of the proposed rule will show, as before, that points 1 and 2 are stable, and that point 3 is unstable. Unlike the conclusions reached from Margand's principle, these points retain the same identity throughout their entire range of existence. For example, point 2′ (figure 4) which was previously found to be unstable, is according to the rule (7) a stable point. Furthermore, the limiting conditions for the stable points are geometrically similar, namely, common tangency of ellipse and reactor characteristic (Margand, in a later paper,[12] calls attention to this fact as a "peculiarity," but without giving an adequate explanation). At this point the conditions for stability and instability simultaneously exist, and a slight variation of the parameters in the proper direction will cause a sudden change in current. Graphically, this means that points 1 and 2 are related to the critical conditions of sudden increase and decrease of current, respectively.

Circuit Characteristics

To demonstrate the method of graphical solutions in the study of circuit characteristics, a few illustrations will now be given. The current as a function of capacitance may be obtained by observing the resulting intersections of the ellipse with the reactor curve as the ellipse is rotated clockwise with increasing capacity, having always a vertical tangent at E/R. (The variation of point 3 is unnecessary to observe and is therefore excluded.) If reference is made to figure 4, it is clear that the current, defined by point 2 for small values of capacitance, first increases continuously to a maximum and then decreases until the limit of stability is reached (point of tangency), beyond which the current suddenly falls to a low value defined by point 1. With further increase of capacitance, the current decreases slowly approaching a constant value. Upon diminishing capacitance, the current retraces the same path in the region of low current values and goes beyond the previous point of collapse, since now point 1 is established and governs the value of current until the point becomes unstable. This will occur when the ellipse is tangent at the knee of the reactor curve, at which point the current suddenly increases to a value defined by point 2. Thereafter with further decrease of capacitance, the original curve is followed. The complete characteristic is similar to those shown in figure 15.

In addition to the current, the reactive voltages may be determined simultaneously by the same process on account of the component nature of the graphical solution. Furthermore, as Rüdenberg[8] has shown, the intersections associated with the upper and lower parts of the ellipse are related to lagging and leading power factor, respectively. The effect of resistance may be observed by varying only the major diameter of the ellipse. If the resistance is sufficiently large, instability is impossible, and a single continuous curve is obtained.

The variation of current as a function of voltage may be studied by observing intersections when both major and minor diameters of the ellipse change while the resistance and capacitance remain constant. With reference to figure 5, it is clear that with rising voltage, the current first increases slowly, then jumps suddenly to a high value (point 2′), and increases continuously thereafter. Upon decreasing the voltage, the current decreases until instability is reached and then falls to a low value. Curves of the same form as those in figure 2 are obtained.

The current as a function of frequency may be adequately described in a relatively simple manner if the reactor voltage is assumed to be directly proportional to fundamental frequency, that is,

$$E_L = \omega F(I) \tag{9}$$

The graphical solution then takes the form

$$F(I) = \pm \frac{1}{\omega}\sqrt{E^2 - (IR)^2} + \frac{I}{\omega^2 C} \tag{10}$$

and the procedure for determining the operating characteristics is analogous to the previous illustrations. In this case, the curve $F(I)$ is constant for all frequencies, whereas both components of the ellipse vary inversely with frequency.

The foregoing examples are indicative of the flexibility of the method of graphical solutions. Although the process of obtaining the circuit characteristics is, from a practical viewpoint, tedious, the presentation gives an unusually clear picture of ferroresonant phenomena. Intrinsically, however, the value of the method lies in the study of critical conditions.

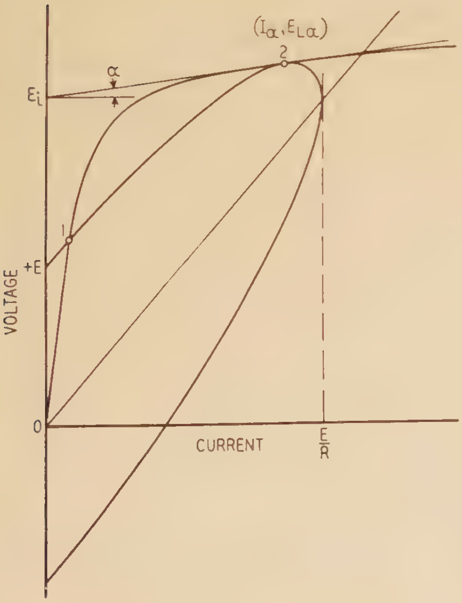


Figure 6. Graphical representation of critical conditions

Critical Quantities

On the basis of the proposed rule, the limit of stability is uniquely defined by common tangency of ellipse and reactor characteristic. In the region of low current (point 1) this condition is possible only in the neighborhood of the knee of the characteristic; hence, the range of critical current values is small. On the other hand, in the region of high current (point 2) the range of critical current values is considerably greater since tangency may occur anywhere along the curve beyond the knee. With these general concepts, the character of critical quantities may be analytically determined. The following treatment deals with point 2, but the results may be applied equally to point 1.

Since, for instability to occur, the ellipse and the reactor must have a common tangent, the intercept of this tangent on the voltage axis E_i (figure 6) may be expressed as

$$E_i = E_{L\alpha} - I_\alpha \left(\frac{dE_L}{dI}\right)_\alpha \tag{11}$$

also

$$\left(\frac{dE_L}{dI}\right)_\alpha \equiv \tan\alpha \tag{12}$$

where $E_{L\alpha}$ and I_α are the critical values of reactor voltage and current at the point of tangency, and $\tan\alpha$, the slope of the tangent.

Employing equation 4, $E_{L\alpha}$ and $(dE_L/dI)_\alpha$ may be evaluated. Thus

$$E_{L\alpha} = +\sqrt{E^2 - (I_\alpha R)^2} + \frac{I_\alpha}{\omega C} \tag{13}$$

$$\left(\frac{dE_L}{dI}\right)_\alpha = \frac{-R^2 I_\alpha}{\sqrt{E^2 - (I_\alpha R)^2}} + \frac{1}{\omega C} \tag{14}$$

Inserting (13) and (14) in (11) and solving for the current, we have

$$I_\alpha = \frac{E}{R}\sqrt{1 - \left(\frac{E}{E_i}\right)^2} \tag{15}$$

The critical capacitance is determined by means of (12), (14), and (15), hence

$$C_\alpha = \frac{1}{\omega\left(\tan\alpha + R\sqrt{\left(\frac{E_i}{E}\right)^2 - 1}\right)} \tag{16}$$

By making use of the expressions for current and capacitance the reactive voltages are obtained.

$$E_{L\alpha} = E\left\{\frac{E}{E_i} + \sqrt{1 - \left(\frac{E}{E_i}\right)^2}\left(\frac{\tan\alpha}{R} + \sqrt{\left(\frac{E_i}{E}\right)^2 - 1}\right)\right\} \tag{17}$$

$$E_{C\alpha} = E\sqrt{1 - \left(\frac{E}{E_i}\right)^2}\left(\frac{\tan\alpha}{R} + \sqrt{\left(\frac{E_i}{E}\right)^2 - 1}\right) \tag{18}$$

Within the limits of assumptions (fundamental frequency), these equations describe the behavior of the critical quantities as functions of the applied voltage, circuit resistance, and characteristic constants of a given iron-core reactor.

Discussion of Equations

A. Region of High Current

In the region of high current characterized by the saturated portion of the reactor characteristic, only the critical conditions for sudden decrease of current exist and are described graphically as the limit of stability at point 2. As this portion of the curve does not include all possible values it is evident that critical quantities related to this point can be defined only within certain limits of applied voltage and circuit resistance. By defining I_0 as the minimum critical current (theoretically, the point at which the tangent leaves the characteristic), the limits of voltage and resistance may be determined by means of equation 15 as follows:

$$I_0 = \frac{E}{R}\sqrt{1-\left(\frac{E}{E_i}\right)^2} \tag{19}$$

Solving for the voltage,

$$E = \frac{E_i}{\sqrt{2}}\sqrt{1 \pm \sqrt{1-\left(\frac{2RI_0}{E_i}\right)^2}} \tag{20}$$

for which

$$R \leq \frac{E_i}{2I_0}$$

in order to obtain a real result. Equation 20 gives two values of voltage, and the limiting case occurs for maximum resistance.

$$R_{max} = \frac{E_i}{2I_0} \qquad E_{max} = E_{min} = \frac{E_i}{\sqrt{2}} \tag{21a}$$

$$R \longrightarrow 0 \qquad E_{max} \longrightarrow E_i,\ E_{min} \longrightarrow 0 \tag{21b}$$

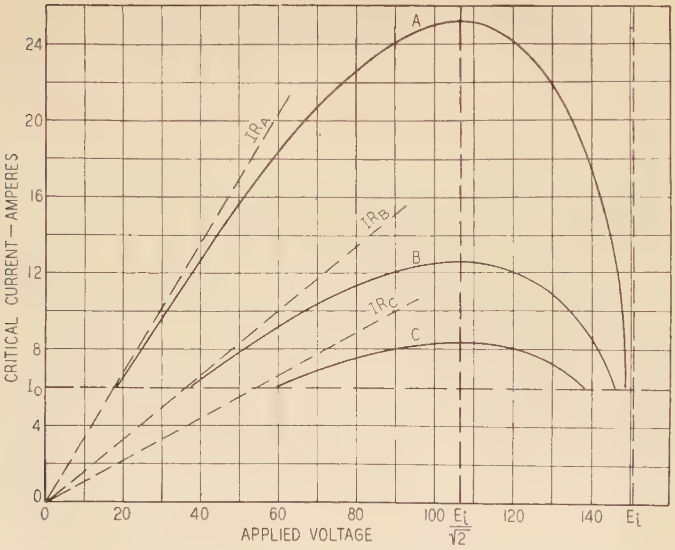


Figure 7. Critical current as a function of voltage. Circuit resistance: A, 3 ohms; B, 6 ohms; C, 9 ohms

Between these limits of applied voltage and resistance instability is possible, and the value of the critical current will be given by (15). It is to be recognized that the above limits are general, and determinate only for the linear portion of the reactor characteristic where E_i is practically constant for a wide range of current values. The maximum critical current is found in the usual manner by differentiation, that is

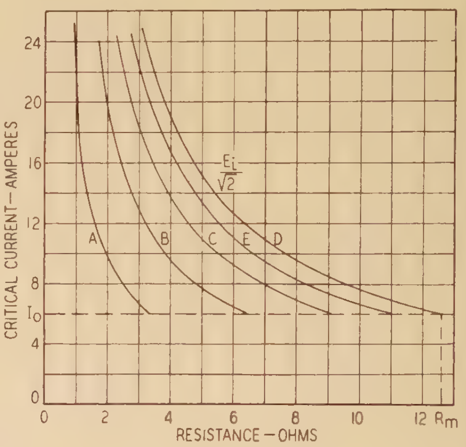
$$\frac{dI_\alpha}{dE} = \frac{1-2\left(\frac{E}{E_i}\right)^2}{R\sqrt{1-\left(\frac{E}{E_i}\right)^2}} = 0$$

giving

$$E = \frac{E_i}{\sqrt{2}},\ I_{\alpha\,max} = \frac{E_i}{2R} \tag{22}$$

Curves showing the variation of critical current as a function of applied voltage and resistance for the saturated portion of the reactor curve (figure 12), neglecting core losses, are given in figures 7 and 8. These curves give a remarkable insight into the phenomena of ferroresonance and call attention to an interesting fact. Contrary to the results of previous methods, the envelope of critical current is not a straight line coinciding with the (IR) line, but a curve having a maximum and dependent upon the values of voltage and resistance. An examination of the experimental curves (figure 9) given by Rouelle[19] illustrates this point well.

Figure 8. Critical current as a function of resistance applied voltage; A, 20 volts; B, 40 volts; C, 60 volts; D, 106.8 volts' E, 130 volts



From consideration of the equation for critical capacitance, it is evident that the working region in this particular case must be limited in a manner corresponding to the current. Since a single value of capacitance will not suffice, a set of limiting values corresponding to the minimum critical current is determined from the limiting values of voltage and resistance obtained from the curves of critical current. Figures 10 and 11 show the variation of critical capacitance as a function of voltage and resistance; the limiting curves are drawn dotted.

For practical purposes, in applying the equation for critical capacitance, an effective angular frequency (ω^1) is introduced in place of (ω) to account for the presence of

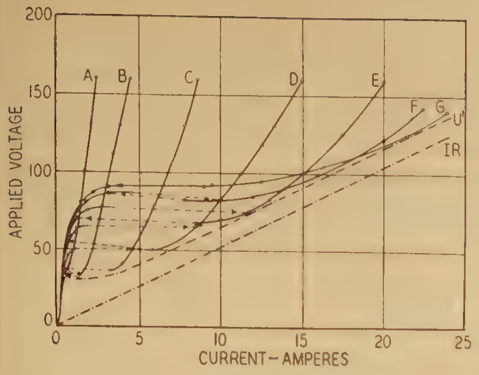


Figure 9. Voltage as a function of current: frequency, 50 cyles per second, resistance 5.2 ohms, capacitance, A, 25 microfarads; B, 40 microfarads; C, 56 microfarads; D, 90 microfarads E, 110 microfarads; F, 126 microfarads; G, 131 microfarads. U′, active component of voltage (experimental results of Rouelle, R. G. E., 1934, page 728)

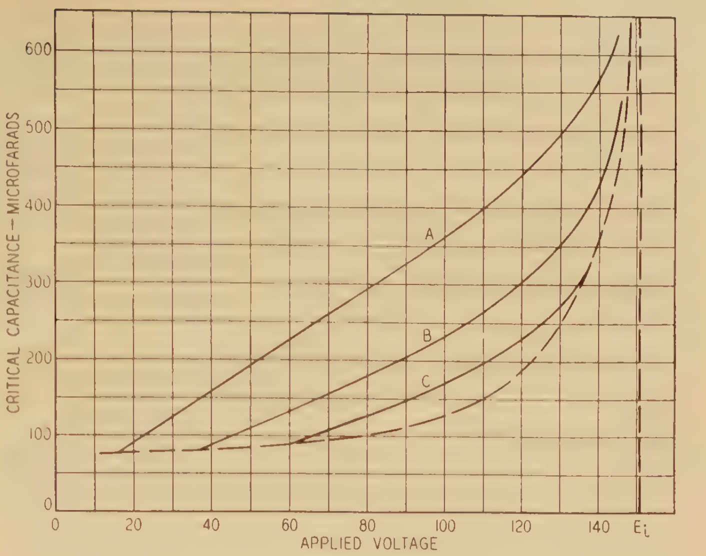


Figure 10 (right). Critical capacitance as a function of voltage. Circuit resistance: A, 3 ohms; B, 6 ohms; C, 9 ohms. Frequency, 60 cycles per second

harmonics. Although the variation of harmonic components of current in ferroresonant circuits is extremely complicated, it has been found that for values of current in the vicinity of breakdown, an effective angular frequency computed from measured values of current, capacitance, and condenser voltage ($\omega^1 = I/E_C C$) is strikingly uniform. In a circuit having a fundamental frequency of 60 cycles per second, the average over a wide range of values of current and capacitance gives

$$\frac{\omega^1}{\omega} = 1.24$$

with a maximum deviation of less than two per cent. For extremely small values of current (point 1), a ratio about nine per cent less is suitable.

Concerning the factors involved in the formulas, the evaluation of circuit resistance is, perhaps, the most important. In addition to the series resistance, consideration must be given to the apparent resistance of the reactor which takes into account the iron losses. This quantity changes both with the degree of saturation and wave form, and it is therefore necessary to have a measure of the variation if accuracy is to be attained.

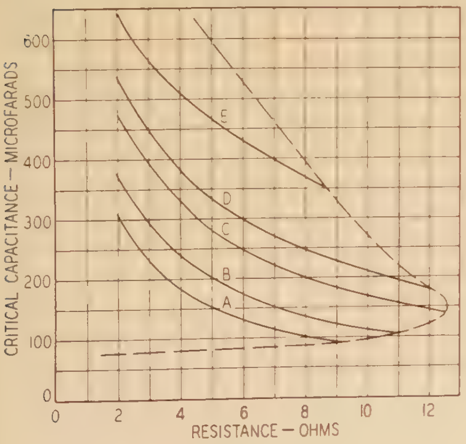


Figure 11. Critical capacitance as a function of circuit resistance. Applied voltage: A, 60 volts; B, 80 volts; C, 106.8 volts; D, 120 volts; E, 140 volts; frequency, 60 cycles per second

As an approximation, it is convenient to determine apparent resistance on the basis of fundamental frequency. The method employed, similar to that of Rouelle,[19] requires power measurements on the reactor with sinusoidal voltage applied. Since under these conditions the average power indicated by the wattmeter is related only to fundamental quantities, the apparent resistance may be defined accordingly as

$$R_A = \frac{P}{I_1^2} \tag{23}$$

where P is the average measured power and I_1, the fundamental component of current at a given value of applied voltage. The variation of apparent resistance and the corresponding fundamental voltage drop (I_1R_A) as a function of effective current are shown in figure 12. The latter quantity is important because in the application of equation 20, total resistance voltage drop required is properly expressed as the sum of the series (external) and the apparent resistance voltage drops. Since the apparent resistance is determined on the basis of fundamental frequency, it follows that the same conditions must be observed for the corresponding voltage drop.

B. REGION OF LOW CURRENT

In the region of low current characterized by the nonlinear portion of reactor characteristic, critical conditions for both sudden increase and decrease of current are theoretically possible. It is necessary therefore, in applying the formulas to determine in what manner the results are related to critical points 1 and 2. In general, it may be inferred from graphical analysis that for point 1, the critical current increases continuously with voltage, whereas, for point 2 a free variation is possible.

Due to the variability of the apparent resistance and the characteristic constants in the nonlinear region, it is advantageous to choose current as an independent variable in order to make a theoretical investigation of critical conditions. For this purpose, equation 20, which gives the voltage as a function of current may be employed. Ob-

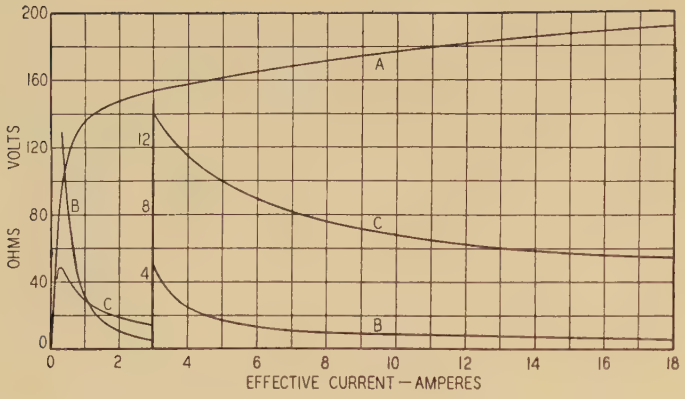


Figure 12. Properties of reactor: A, volt-ampere curve; B, apparent resistance; C, apparent resistance voltage drop (I_1R_a)

viously two values of voltage are possible for every value of current, but only one of these may be associated with point 1 if it exists, the other with point 2. The existence of a critical point 1 depends upon the value of current and resistance in such manner that the voltage given by (20) (positive sign) increases continuously with critical current. This means that only a certain set of critical current values can be defined by this point, and its range, therefore, must be determined by the limiting conditions which are fixed by minimum and maximum values of critical current. With respect to the minimum value the limits of applied voltage and resistance are bound by the same restrictions as in the previous case (21*a*), but are of an indeterminate nature. For the maximum value, these limits are likewise indefinite and can be found only by successive computation; it is the point at which the voltage ceases to increase with critical current (upper limiting value). For critical current values greater than this maximum, both values of voltage given by (20) are clearly associated with the critical point 2. Consequently, the locus of critical current with respect to voltage determined for the nonlinear region of the reactor characteristic includes two distinct portions according to the type of critical condition.

Curves showing the variation of critical current as a function of voltage, taking into account apparent resistance of the reactor (figure 12), are given in figure 13. The solid and dotted portions of the curves are related to critical points 1 and 2, respectively; the dividing line XY is the envelope of limiting values of voltage between which both types of critical conditions are possible. The corresponding curves for critical capacitance are given in figure 14.

The general form of these curves discloses several interesting properties of ferroresonant circuits. Although the abrupt changes in current have been observed to occur alternatively as a pair, the curves give evidence of a possibility of achieving only breakdown of current at low values of voltage beyond the limiting value without the corresponding sudden increase of current. Another interesting feature is that critical current in the region characterized by point 1 increases with resistance, although not appreciably except at higher voltages. Likewise, critical capacitance changes only slightly with increased resistance. In this case, however, there is a nonuniform variation which may be ascribed to the effect of apparent resistance. These families of curves, together with those previously discussed form the complete envelope and illustrate the typical variation of the critical quantities.

Application of Theory

The ferroresonant circuit presents to the engineer a wide variety of possibilities that are useful in relay and control problems. The extent to which these may be utilized is apparent from the circuit properties shown in the preceding curves. In this connection, therefore, it is intended only to suggest what might be done and to give some illustrative examples.

1. Suppose it is desired to design a ferroresonant circuit such that for a given value of series resistance the maximum change in current occurs when the circuit becomes unstable.

If, for example, the case of breakdown of current is considered, the necessary conditions are defined by (22) in which E_i is the only unknown quantity. Assuming that the critical current is related to the saturated portion of the volt-ampere curve of the reactor, the intercept value of

Figure 13. Variation of critical current in region of low current. Series resistance: A, 0 ohms; B, 9 ohms; C, 15 ohms; D, 25 ohms

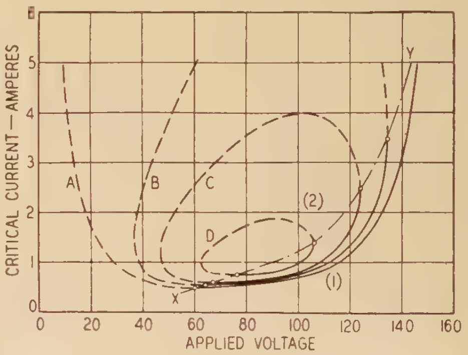
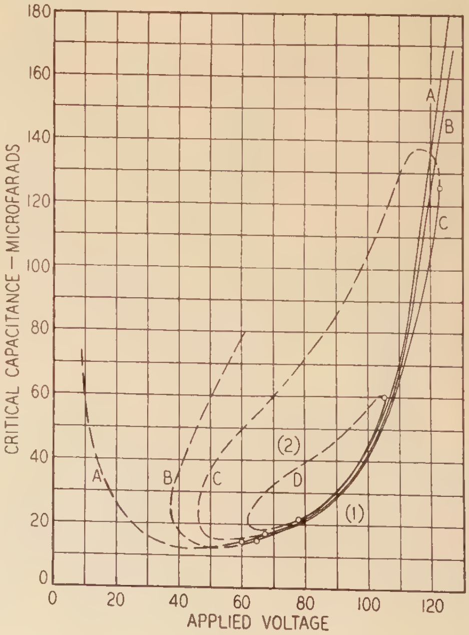


Figure 14. Variation of critical capacitance in region of low current. Series resistance: A, 0 ohms; B, 9 ohms; C, 15 ohms; D, 25 ohms; frequency 60 cyles per second



the tangent is, from figure 12, $E_i = 151$ volts. Thus, if the series resistance, $R_s = 9$ ohms

$$I_{\alpha\,max} = \frac{E_i}{2R} = \frac{151}{18} = 8.38 \text{ amperes}$$

At this current value, the apparent resistance of the reactor is, $R_A = 1$ ohm, which is to be added to the series resistance. Since E_i is about the same as before, the corrected value of current becomes

$$I_{\alpha\,max} = \frac{151}{20} = 7.55 \text{ amperes}$$

and the required applied voltage

$$E = \frac{E_i}{\sqrt{2}} = \frac{151}{\sqrt{2}} = 106.8 \text{ volts}$$

The required circuit capacitance is given by (16) in which $\omega' = 468$ radians per seconds ($f = 60$ cycles per second, $\omega'/\omega = 1.24$); further corresponding to E_i, $\tan\alpha = 2.7$ ohms. Thus,

$$C_\alpha = \frac{1}{468(2.7 + 10)} = 168 \text{ microfarads}$$

If, instead of breakdown, circuit instability with respect to the sudden increase of current were considered, the applied voltage necessary for the maximum change of current is somewhat higher than in the previous case. Evidence of this fact is given in figure 9, curve *e*. To make the computation, therefore, it is only necessary to select a few current values about the knee of the volt-ampere curve that gives by means of (20) a value of voltage about ten per cent higher than in the previous case. This solution also determines the proper characteristic constants to be used in the equation for critical capacitance.

2. Suppose that it is desired to design a ferroresonant circuit that is sensitive to small changes in voltage yet single valued in character (for example, curve *g*, figure 9). As this condition is related to the upper limiting value of voltage (figure 13), it is necessary to compute several values of voltage by means of (20) corresponding to current values selected above the knee of the volt-ampere curve. The required value is that for which the voltage becomes a maximum with respect to current.

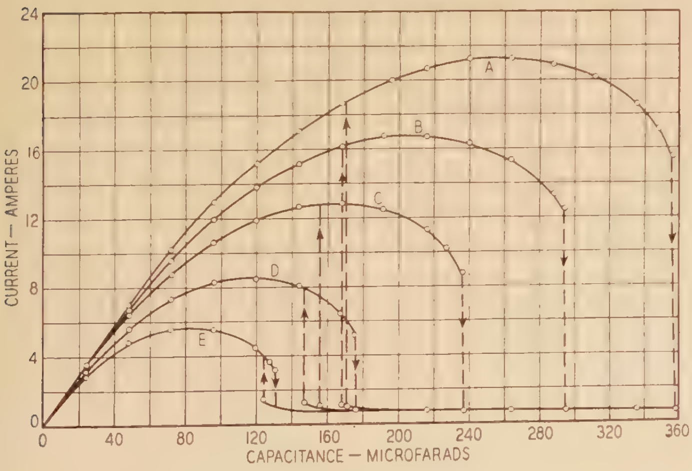


Figure 15. Experimental results; current as a function of capacity. Series resistance: A, 3.88 ohms, B, 5.02 ohms; C, 6.65 ohms; D, 9.9 ohms; E, 14.75 ohms. Applied voltage, 121 volts; frequency 60 cycles per second

For example, let $R_s = 15$ ohms. Take $I = 1.5$ amperes then from figure 12, $E_i = 127$ volts and $I_1R_A = 22$ volts; $(IR)_{\text{total}} = 22.5 + 22 = 44.5$ volts.

From (20)

$$E = \frac{127}{\sqrt{2}}\sqrt{1 + \sqrt{1 - \left(\frac{89}{127}\right)^2}} = 118.5 \text{ volts}$$

Similarly,

$I = 2$ amperes, $E = 123$ volts
$I = 2.5$ amperes, $E = 123.5$ volts
$I = 3$ amperes, $E = 122.5$ volts

Hence, the required voltage is 123.5 volts and the corresponding constants are: $E_i = 137$ volts, $\tan\alpha = 5.75$ ohms and $R_A = 7$ ohms

therefore,

$$C = \frac{1}{468\left(5.75 + 22\sqrt{\left(\frac{137}{123.5}\right)^2 - 1}\right)} = 131 \text{ microfarads}$$

3. In the general problem, we are concerned with the determination of critical current and capacitance for a given value of applied voltage and series resistance. For this case, the results of experiments on a ferroresonant circuit employing a given reactor are available (figure 15) so that a quantitative check on the theory may be obtained.

For example: $E = 121$ volts, $R_s = 6.65$ ohms (experimental values). Neglecting the apparent resistance of the reactor, a trial calculation is made using the value of intercept voltage, $E_i = 151$ volts, determined from the linear portion of the volt-ampere curve of the reactor. Thus from (15)

$$I_\alpha = \frac{121}{6.65}\sqrt{1 - \left(\frac{121}{151}\right)^2} = 10.9 \text{ amperes}$$

For this value of current, E_i is about the same as assumed above and $R_A = 0.95$, so that the total series resistance becomes 7.60 ohms. The corrected value of critical current is therefore

$$I_\alpha = \frac{121}{7.6}\sqrt{1 - \left(\frac{121}{151}\right)^2} = 9.53 \text{ amperes}$$

From test it is found (see curve *c*, figure 15), $I_\alpha = 8.9$ amperes.

Computing the critical capacitance ($f = 60$ cycles per second, $\omega' = 468$ radians per second, $\tan\alpha = 2.7$ ohms)

$$C_\alpha = \frac{1}{468\left(2.7 + 7.6\sqrt{\left(\frac{151}{121}\right)^2 - 1}\right)} = 255 \text{ microfarads}$$

From test, $C_\alpha = 238$ microfarads

The errors in both cases are seven per cent, approximately.

To find the critical current for the point of sudden increase, it is convenient to employ equation 20 and make a

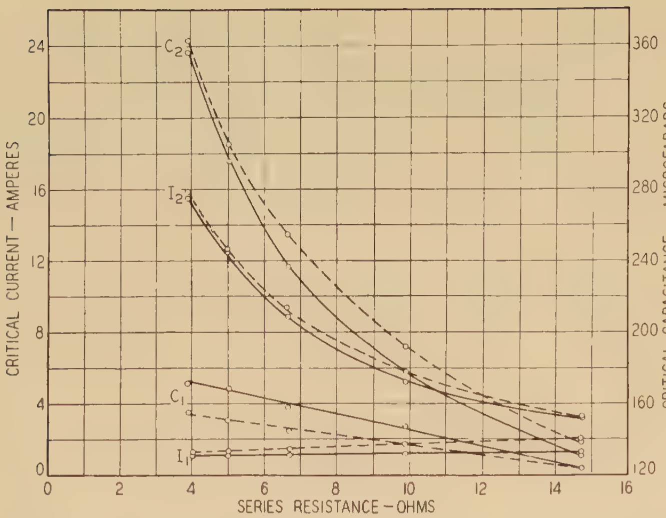


Figure 16. Comparison of measured (solid curves) and computed (dotted curves) values of critical current and capacity as a function of series resistance

few trial substitutions of current values. This is necessary since the characteristic constants change sharply with current about the knee of the volt-ampere curve of the reactor. The solution is given when the calculated voltage is equal to the applied voltage. Since the proper characteristic constants are now available, the calculation of critical capacitance follows directly.

Without going through the computations, reference is made to figure 16 in which a comparison of measured and calculated results is given. The error between these values is confined within reasonable limits and is due primarily to the presence of harmonics, particularly in the reactor voltage, which influence the value of apparent resistance.

Conclusion

The calculation of critical quantities by means of the given formulas is quite simple, although in some instances preliminary computation is required. In any case, the trial substitutions are made with respect to one quantity, and having once determined this quantity, the corresponding critical values of all the other quantities may be readily calculated. This method of obtaining critical quantities is obviously much superior to previous methods which require the determination of families of curves, as in figure 2, from which the desired information is then obtained.

In the study of critical conditions in ferroresonance, this investigation has demonstrated that the characteristic discontinuities of current are not isolated phenomena, but are directly related and occur under parallel circumstances. The principles governing stability and instability have been clearly set forth in the proposed rule for stability, and as a consequence, simple formulas defining critical quantities have been obtained. The rule for stability may also be applied in more complex problems such as the influence of superimposed d-c excitation upon ferroresonance. Critical conditions, as we have seen, are not only dependent upon the properties of the reactor, but also upon the applied voltage and resistance. These facts make for a clear understanding of ferroresonant phenomena and enable the engineer to design circuits to operate under optimum conditions.

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Overvoltages Caused by Unbalanced Short Circuits

Effect of Amortisseur Windings

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Introduction

IN CASE of unbalanced faults on power systems, the voltage on the unfaulted phase or phases may often reach very high values. There may be an overvoltage caused by the short circuit itself and a further overvoltage caused by the clearing of the fault. In the present paper only the first type will be discussed. These unfaulted phase overvoltages may vary widely with the type of fault, the system constants and arrangement, and the kinds of synchronous machines affected. However, in faults not involving ground the presence of overvoltages depends on the fact that the synchronous machines supplying the fault current are not electrically symmetric-rotor machines. Thus, these overvoltages may be largely eliminated or reduced by a properly designed amortisseur winding. Even in case of overvoltages caused by faults involving ground there is a considerable reduction with such an amortisseur winding.

Purely from the standpoint of reducing overvoltages it is evident that such rotor windings are very desirable, and it is advisable to examine carefully each particular case in order to determine how far in the direction of the ideal amortisseur it is economically desirable to go. It is the purpose of this paper to present comparative information on overvoltages caused by one type of fault on a salient-pole synchronous machine with various kinds of amortisseur windings in order to provide one basis for evaluating quantitatively the relative merits of the different types of amortisseur windings. The qualitative effects are of course already known. Mandl[1] has made an extended study of overvoltages caused by single-phase short circuits with terminal capacitance and has shown the existence of resonant points and the possibility of obtaining high voltages on the unfaulted phase of machines with electrically unsymmetrical rotors. Wagner[2] has recently made an experimental study of similar cases. Doherty and Nickle[3] have shown that the magnitude of open-phase voltage during single-phase short circuit of an open-circuited machine is a function principally of the ratio of quadrature-axis reactance to direct-axis reactance, while Park and Skeats[4] have similarly shown how this ratio affects recovery voltage. A later investigation[5] of double line-to-ground faults has given expressions for the open phase voltage for that case. The present paper takes into account more exactly than has hitherto been done the effects of amortisseur windings and of connected terminal capacitance and gives quantitative overvoltage data over a range of machine and system constants.

The practical importance of the study is brought out by lightning arrester and bus failures which could not be reasonably explained except by the high dynamic voltages described in this paper. In one case tests made subsequent to a failure have definitely shown the source of trouble to be these voltages.

In order to obtain the information reported here a detailed study of line-to-line short circuits on a synchronous machine connected to various capacitances and provided with many different designs of amortisseur circuits was made on the differential analyzer[6] at the Moore School of Electrical Engineering of the University of Pennsylvania. By means of the differential analyzer it was possible (1) to take into account most of the significant factors, the effects of which it would be practically impossible to calculate exactly and (2) to vary the machine and line characteristics easily over a wide range, which would be impossible in field tests.

A line-to-line short circuit was studied since this may result in some of the highest overvoltages, and it was not primarily the object to study the effect of various kinds of short circuits but rather the effects of various kinds of amortisseur windings.

Conclusions

As a result of this study the following conclusions have been drawn.

1. High voltages may appear on the unfaulted phase of a synchronous machine with unsymmetrical rotor during line-to-line short circuits.

2. The principal determining factor for the magnitude of overvoltages caused by line-to-line short circuits is the ratio (x_q''/x_d'') of quadrature-axis subtransient reactance to direct-axis subtransient reactance. This ratio is a function of the amortisseur characteristics.

3. The maximum possible overvoltage caused by a line-to-line short circuit on an open circuited machine is given very closely by the formula[3]

$$e_{\max} = 2\frac{x_q''}{x_d''} - 1 \tag{1}$$

4. The overvoltage may be considerably increased over the value of equation 1 by terminal capacitance, the worst condition arising when the capacitive reactance is approximately nine times the negative sequence reactance of the generator. The amount of increase of

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[1] For all numbered references, see list at end of paper.

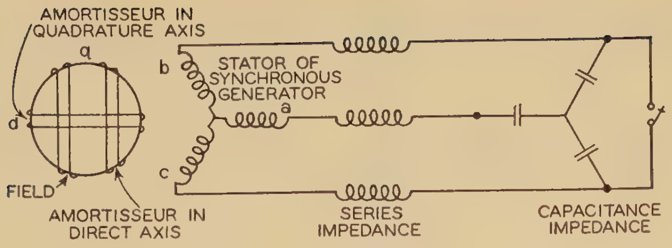

AMORTISSEUR IN QUADRATURE AXIS
q
b
STATOR OF SYNCHRONOUS GENERATOR
a
d
c
FIELD
AMORTISSEUR IN DIRECT AXIS
SERIES IMPEDANCE
CAPACITANCE IMPEDANCE

Figure 1

Table I

Case	x_d''	x_q''	$\frac{x_d''+x_q''}{2}(=x_2)$	x_q''/x_d''	e_0	e_c	$\frac{e_c-1}{e_0-1}$
1	0.439	0.456	0.447	1.04	1.08	1.6	7.5
2	0.456	0.490	0.473	1.07	1.15	2.0	6.66
3	0.478	0.544	0.511	1.14	1.28	2.85	6.6
4	0.489	0.567	0.528	1.16	1.32		
5	0.439	0.516	0.477	1.17	1.35	3.15	6.15
6	0.456	0.553	0.504	1.21	1.42	3.75	6.55
7	0.478	0.616	0.547	1.29	1.58	5.15	7.15
8	0.489	0.650	0.569	1.33	1.66	6.1	7.73
9	0.556	0.900	0.728	1.62	2.24	8.0	5.65

this maximum possible overvoltage depends on the field and armature short circuit time constants, being small when either or both of these quantities are small. For large waterwheel generators the field time constant is ordinarily very large and so may be assumed infinite with little error. On the other hand the terminal capacitance will ordinarily be that of a connected open transmission line and so will be accompanied by a somewhat increased armature circuit resistance which will tend to reduce the armature time constant and consequently the overvoltage.

5. If a salient-pole generator is to be subject to the possibility of connection to an open transmission line of relatively large capacitance or of open circuited operation the ratio x_q''/x_d'' should be kept within limits determined on the basis of permissible overvoltage.

6. The overvoltage will in general be greatly reduced by connection of the salient-pole machine to a power system.

7. The ratio x_q''/x_d'' may be determined by test from single-phase static impedance measurements. The ratio should either be measured at a current equal to the expected rms displaced single-phase short-circuit current or several points taken in order to extrapolate to this current.

Description of System

The system studied is shown in figure 1, the capacitance and series impedance being included to represent approximately the effect of a connected transformer and open transmission line.

The amortisseur circuits of the machine were represented by two windings, one in the field axis of the rotor and one in the quadrature axis, the mutual inductance of the field, direct-axis amortisseur, and direct-axis armature winding being a single quantity. The synchronous machine may therefore be represented by the equivalent circuits of figure 2, in which the machine characteristics are specified by the mutual and leakage reactances of the various windings. The field resistance was neglected, that is, constant flux linkages were assumed in the field circuit, since with the long field time constants of large synchronous generators the change of field flux linkages in the first few cycles after short circuit will be inappreciable and the short circuits will usually not last more than a few cycles. Also the effect of saturation was neglected in so far as it would tend to vary the reactance during the period of short circuit. However it is assumed that the reactances specified apply to saturation conditions corresponding to single-phase short-circuit current. The machine is assumed to conform to the theory of the ideal synchronous machine as defined by Park.[7]

The machine constants were taken as average values for salient-pole (waterwheel) generators, except for the constants of the additional rotor circuits, which were varied over a wide range. The constants (see nomenclature and figure 2 for definition of symbols) used in this study were, in per unit of the machine rating,

$x_l = 0.20$ $\qquad$ $r_{kd} = 0.02$

$x_{ad}' = \dfrac{x_{ad}x_f}{x_{ad} + x_f} = 0.18,\ x_d' = 0.38$ $\qquad$ $r_{kq} = 0.02$ for cases 1–4

$x_{aq} = 0.52,\ x_q = 0.72$ $\qquad$ $r_{kq} = 0.04$ for cases 5–8

Case	x_{kd}	x_{kq}
1	0.09	0.09
2	0.14	0.14
3	0.22	0.24
4	0.29	0.29
5	0.09	0.18
6	0.14	0.26
7	0.22	0.43
8	0.29	0.56
9	∞	∞

Cases 1 to 4 apply to amortisseurs with substantially symmetric leakage reactances, while cases 5 to 8 apply to amortisseurs with quadrature-axis leakage reactance substantially twice those of the direct axis. Case 9 represents a machine with no amortisseur. In all of these cases the series impedance (figure 1) consisted of a reactance of 0.18 per unit and a resistance of 0.05 per unit, except as otherwise indicated. Also in cases 2 and 6 the amortisseur resistances were varied.

The electrical system of figures 1 and 2 may be represented by the set of simultaneous equations of appendix *A*, which were set up on the differential analyzer and solved for the unfaulted phase terminal voltage e_a.

In order fairly to compare the various types of machines, overvoltages were determined for each machine over a range of capacitive reactance, corresponding ap-

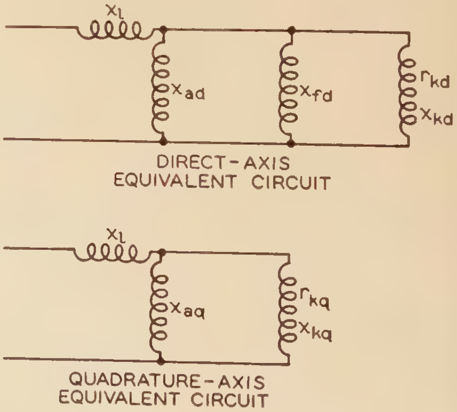


Figure 2

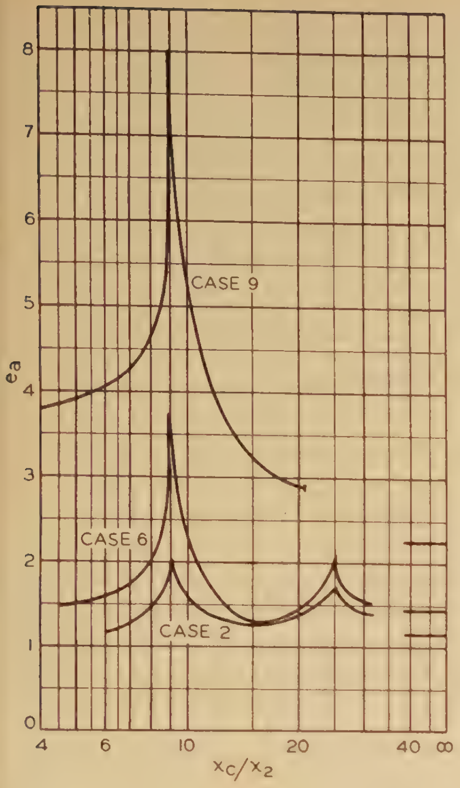


Figure 3. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of amortisseur winding

proximately to transmission lines of various voltages and lengths. The range covered varied somewhat but was in general about $3\,x_2 < x_c < 30\,x_2$, where x_2 is the average of the direct- and quadrature-axis subtransient reactances including the external reactance.

Results

Figures 3 to 5 show some of the results obtained. On these curves are recorded the maximum voltage reached in the first four or five cycles following short circuit, as read from the curves of instantaneous voltage versus time plotted by the differential analyzer.

It is seen that as a function of the ratio of line capacitive reactance to average generator subtransient reactance (or negative-sequence reactance) the overvoltage curves have the same characteristic shape for all machines. Voltage peaks are observed at $x_c/x_2 = 9$ and $x_c/x_2 = 25$, which correspond to series resonance of the line capacitance with the negative-sequence reactance for the third and fifth harmonics, respectively.

Figure 3 shows how the addition of the amortisseur winding of case 6 reduces the maximum voltage to about half of the value obtained with no amortisseur winding, and also the further reduction obtainable by the use of the amortisseur of case 2. This latter is particularly noticeable at the resonant point $x_c/x_2 = 9$. The overvoltages obtained when line capacitance is not considered are indicated at the extreme right of the figure. Line capacitance is seen in general to increase the voltages obtained, especially when it is great enough to approach the point of third-harmonic resonance.

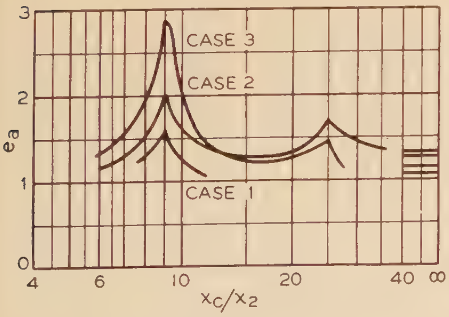


Figure 4. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of amortisseur reactance

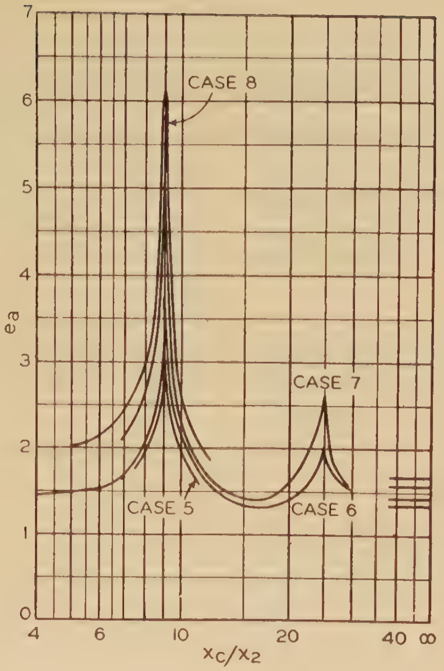


Figure 5. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of amortisseur reactance

Figures 4 and 5 show the effect of variation of the amortisseur leakage reactances. Figure 4 covers the range of amortisseurs with symmetric leakage reactances (cases 1–4), while figure 5 covers the range of unsymmetrical amortisseurs (cases 5–8). As would be expected, the low reactance windings are the most effective. As an indication of the relative effectiveness of the several amortisseur windings table I is given.

The subtransient reactances include the external inductive reactance. The e_0 column contains the maximum open-phase voltages obtained by the formula

$$e_0 = 2\,\frac{x_q''}{x_d''} - 1 \tag{1}$$

of Doherty and Nickle,[3] neglecting capacitance and assuming constant amortisseur flux linkage and short circuit at the instant of maximum flux linkage in the shorted phases. The e_c column contains the maximum voltages found by means of the differential analyzer under the worst condition of connected external capacitance $x_c/x_2 = 9$. The last column gives the ratio of maximum excess voltage $(e_c - 1)$ with capacitance to the excess voltage $(e_0 - 1)$ for an open-circuited machine. This ratio is seen to be very nearly a constant quantity since the armature time constant was not varied very much (r_a = constant = 0.05) and the field resistance was constantly zero. Since the maximum voltage e_c occurs several cycles after short circuit it will be somewhat reduced if allowance

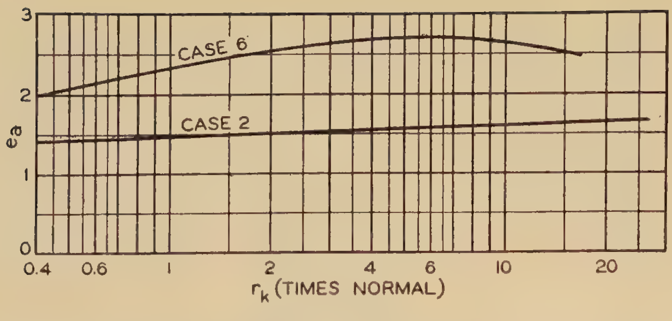


Figure 6. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of amortisseur resistance

Case 6—x_c/x_2 = 9.9, x_q''/x_d'' = 1.21
Case 2—x_c/x_2 = 10.6, x_q''/x_d'' = 1.07

is made for the decay of field flux linkage, while on the other hand the voltage e_0, which occurs in the first cycle, will not be appreciably affected.

In general the overvoltages depend principally on the reactances x_d'', x_q'', x_c; the effect of the resistances r_{kd}, r_{kq}, r_a being of secondary importance except in the case of r_a at or near one of the resonant points (particularly at $x_c/x_2 = 9$). Figure 6 shows how at a particular value of line capacitance, and for the machines of cases 2 and 6, the overvoltage is affected by changes of the amortisseur resistances in the ratio of 32 to 1. For the cases investigated, amortisseur resistance has evidently very little effect; there is a slight increase of overvoltage with increasing amortisseur resistance.

The effect of line resistance r_a in reducing the magnitude of overvoltage is seen in figure 7 for the machine of case 9 with a rather large line capacitance. The case of figure 7 is not a resonant condition, so that line resistance, unless very high, reduces the voltage only about 10 or 20 per cent. At a resonant point the line resistance has much more effect, the voltage in some cases being almost inversely proportional to resistance.

In figure 8 are given some typical voltage-time curves obtained. Inspection of these curves shows that the voltage consists principally of a term of fundamental frequency and one having the frequency $\sqrt{x_c/x_2}$, the latter corresponding to the "average natural frequency" of the series circuit formed by the unfaulted phase. That is, the frequency of the principal natural frequency term can be calculated with good accuracy by neglecting the fact that the machine has an unsymmetrical rotor and using the average of the direct- and quadrature-axis subtransient reactances.

Another point brought out by figure 8 and by the many other voltage curves taken is that with amortisseur windings the voltages in the first few cycles, if the decay of field flux linkages is neglected, are only slightly if at all higher than the values during later cycles after the transients caused by the amortisseur and stator resistances have died away. In fact, in the region where the highest overvoltages are likely to occur, i.e., near $x_c/x_2 = 9$, the voltage requires several cycles to build up to its peak value, which occurs after armature transients have vanished.

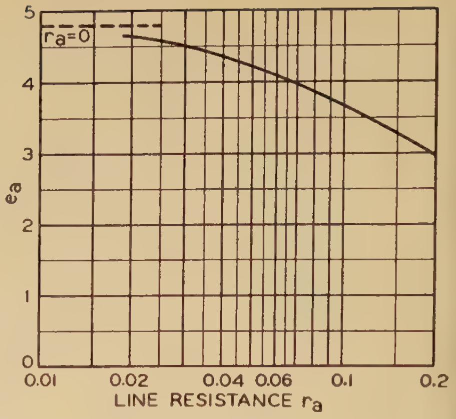


Figure 7. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of line resistance

Case 9—x_c/x_2 = 6.86

The overvoltages were always highest for short circuit at the instant of maximum flux linkage in the shorted phases except near the third harmonic resonant point where there was no appreciable difference in overvoltage with angle. Therefore, after sufficient data were obtained to settle the question, all overvoltages were determined for short circuits at maximum linkage.

Calculation of Overvoltages

Consideration of the form of the voltage curves and of the rather small effect of rotor resistance leads one to the conclusion that for machines with amortisseur windings a good approximation to the voltage may be had by neglecting rotor resistances and also neglecting armature transients. If this is done a relatively simple method of calculation is available (see appendix *B*), the results of which show approximate agreement with those found by the differential analyzer. Figure 9 presents a comparison of calculated and analyzer results for case 6.

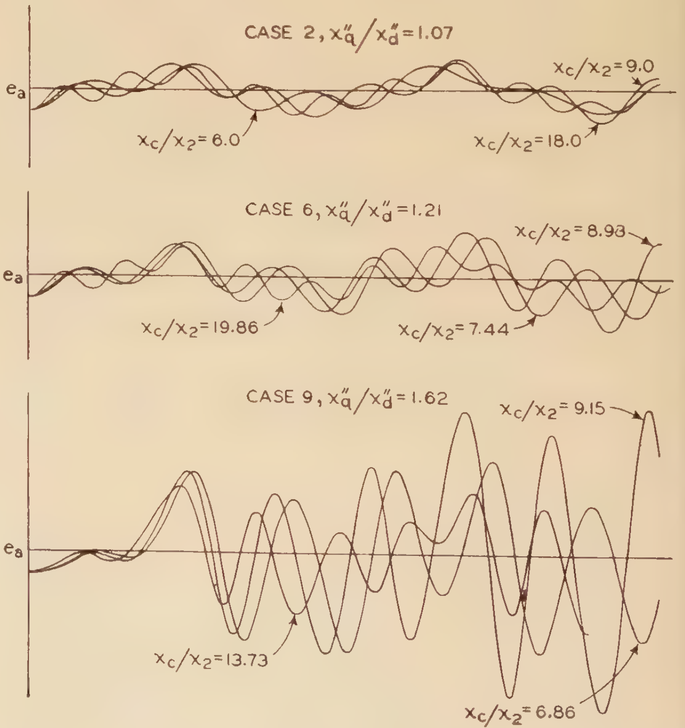


Figure 8. Voltage-time curves determined by differential analyzer

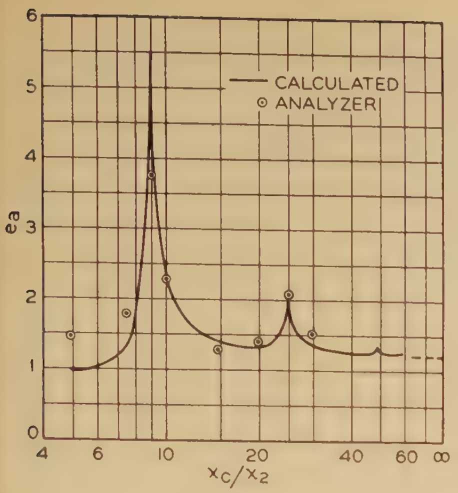


Figure 9. Comparison of calculated steady-state overvoltages with differential analyzer results

Case 6—x_q''/x_d'' = 1.21

In the case of the synchronous machine with no amortisseur windings (case 9) the armature transients had to be considered in order to obtain a reasonable check. Figure 10 shows a curve of voltage versus time determined by the differential analyzer compared with a step-by-step solution of the equations of appendix *B* for $r_a = 0$, $x_c = 5$, and no amortisseur. The complete solution including armature transients has also been found analytically as explained in appendix *B* and points calculated by the formula developed are shown on figure 10.

Equations 8*b* and 9*b* of appendix *B* show that the voltage is a function of the three ratios y/x, r/x, x_c/x. y/x is simply related to the ratio x_q''/x_d'' by the formula,

$$\left(1+\frac{y}{x}\right)\left(1+\frac{x_q''}{x_d''}\right) = 2 \qquad (2)$$

while x is very nearly the negative-sequence reactance x_2. The voltage produced is thus a function of x_q''/x_d'', the

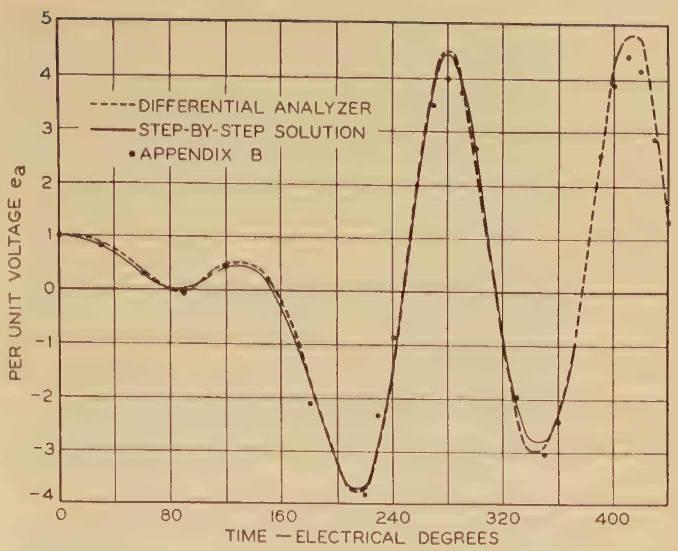
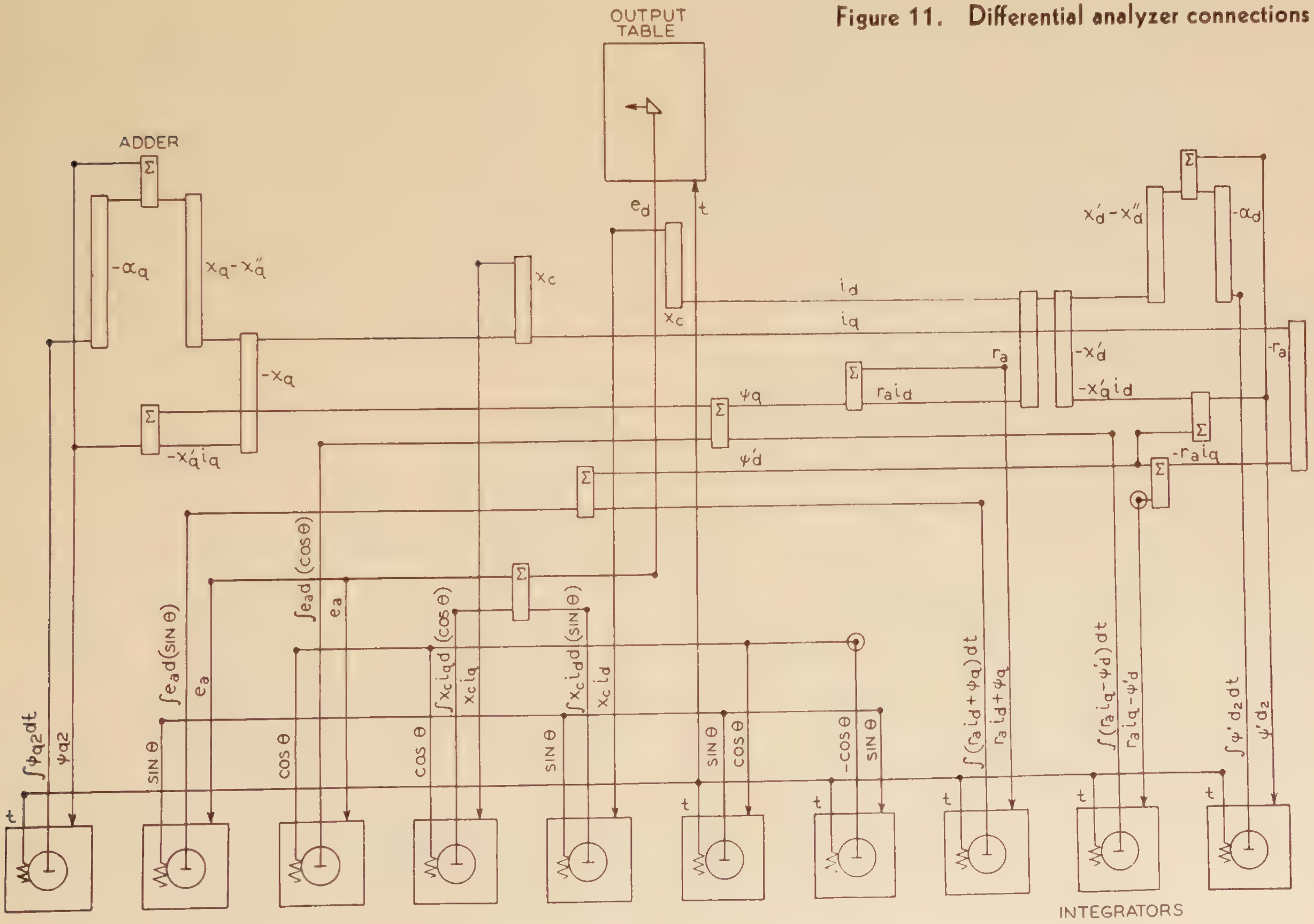


Figure 10. Overvoltage following line-to-line fault on salient-pole synchronous generator

Figure 11. Differential analyzer connections



armature short-circuit time constant x_2/r, and the ratio x_c/x_2. Moreover, if only the maximum possible overvoltage obtainable is of interest, x_c/x_2 will always be very nearly 9, so the voltage is a function only of x_q''/x_d'' and x_2/r. This however neglects all rotor decrement factors.

Comparison With Test Results

In order to check the results obtained by calculation and by the differential analyzer several tests were made. In general the maximum voltages recorded in test have been somewhat lower than those indicated by the analyzer. This is believed to be principally because the machines tested had rather low field time constants (about one second open circuit). The rapid decay of field flux prevented the high build-up of voltage at resonant points so that the maximum voltage always occurred in the first two or three cycles. Three methods of comparing tests and calculated results were therefore used. One was to increase the voltage ordinates obtained in test oscillograms in inverse proportion to the field flux, another was similarly to decrease the analyzer curves or more simply to read the analyzer voltage peak at the point of maximum test voltage. Since the maximum voltage measured in test always occurred in a very short time it was not necessary to correct for field flux in the last method.

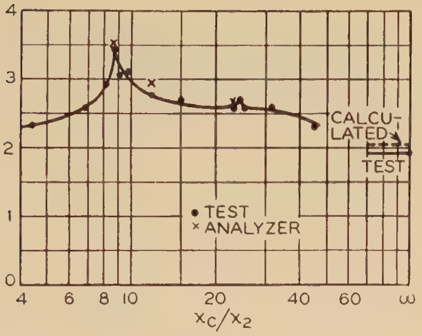


Figure 12. Overvoltage due to line-to-line fault on synchronous machine — comparison of test and analyzer results

$x_q''/x_d'' = 1.52$

Figure 12 shows a comparison of a curve of maximum test overvoltage with the overvoltage obtained by the differential analyzer in the same time. The overvoltage with no capacitance is also shown and compared with the calculated value. In this case the ratio $(e_c - 1)/(e_0 - 1)$ is $2.45/0.92 = 2.66$ instead of about six as would be obtained with infinite field time constant and a lower armature resistance.

Figure 13 shows a comparison of test overvoltages obtained on the same machine with different amortisseur windings. It is seen that for $x_q''/x_d'' = 1.0$ there is no appreciable overvoltage while for $x_q''/x_d'' = 1.7$ the voltage reaches 4.05 times normal at the third-harmonic resonance point. With no capacitance the maximum voltage is 2.32. Here the ratio $(e_c-1)/(e_0-1) = 3.05/1.32 = 2.3$.

Figure 14(c) shows the oscillogram from which the maximum overvoltage at the highest peak of figure 13 was obtained. The oscillogram shows line-to-line voltage while figure 13 shows line-to-neutral voltage, so the ratio of voltage after short circuit to voltage before short circuit read from the oscillogram is 0.866 times the ratio plotted in figure 13. A few other typical oscillograms are also given in figure 14.

In the tests it was found that the values of subtransient reactance to be used in computing overvoltage could be determined most easily and accurately by a static single-phase impedance test. Figure 15 shows the test ratios for the machine of figure 13. The high ratio is seen to be affected by saturation and the value used in checking the test overvoltage curves was that corresponding to the calculated offset root-mean-square single-phase short-circuit current. The tests shown in figure 13 were taken at reduced voltage. For short circuits at full voltage the ratio x_q''/x_d'' is about 1.5 and the overvoltage is correspondingly reduced.

Discussion

A. THE RATIO x_q''/x_d''

It has been brought out above that overvoltage is principally a function of the ratio x_q''/x_d''. However, except for faults directly at the machine terminals there will be a reactance in series with the machine reactance. Therefore, in these cases a low average subtransient reactance is also desirable since for the same ratio x_q''/x_d'' at the machine terminals the effective ratio at the fault will be lower with lower machine reactance. Thus aside from their effect on the ratio as measured at the machine terminals, amortisseur windings will usually reduce the overvoltage produced.

The ratio x_q''/x_d'' is always highest at the machine terminals. It does not necessarily follow that faults directly at the terminals will always result in the highest voltages. In the circuit of figure 1, the reactance should be taken to the point of fault while the capacitance is, to a first approximation, that of the whole open line or lines. For a particular case it is therefore conceivable that third-harmonic resonance may occur for faults out on the line, and that the resultant voltage may be higher despite the decreased effective ratio x_q''/x_d''. In practice, however, we must usually take into consideration all possible

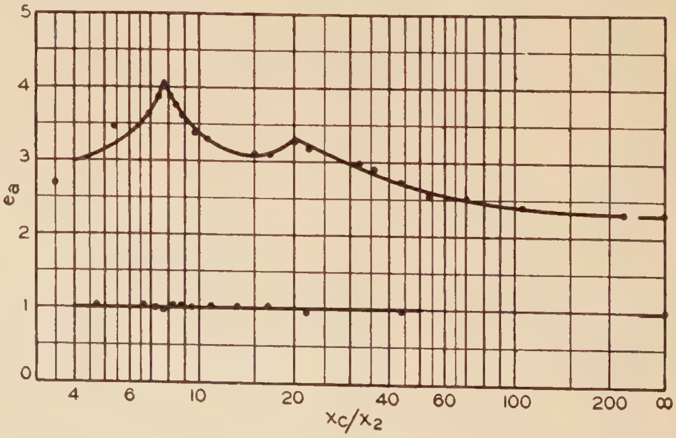


Figure 13. Overvoltage due to line-to-line fault on synchronous machine—test results

Upper curve—$x_q''/x_d'' = 1.7$ Lower curve—$x_q''/x_d'' = 1.0$

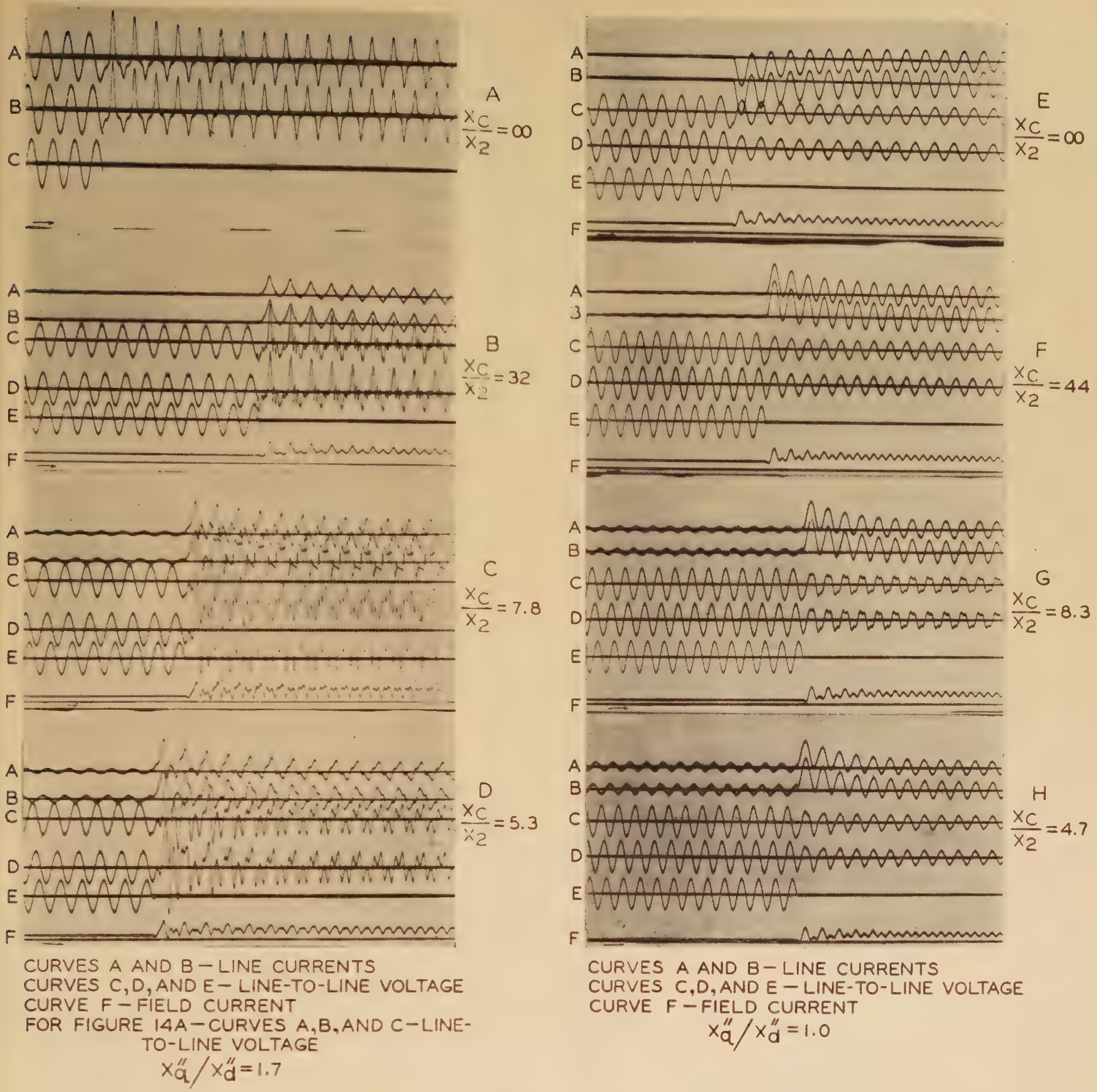


Figure 14. Oscillograms of line-to-line fault on salient-pole synchronous machine

connected amounts of line. The highest possible overvoltages will then occur for faults at the machine terminals.

B. Factors Limiting Overvoltage

The highest overvoltages indicated in this paper will not in general occur in practice. Saturation will limit the voltages to a certain extent and protective equipment will function. The saturation effect however will not be nearly as great as might be supposed from an inspection only of the magnitude of the voltage peaks, since the fundamental component is usually only slightly higher than normal, the highest values recorded consisting principally of a third-harmonic component. Lightning arresters may be expected to be damaged by the high sustained voltages. Also in many cases the machine will be connected to a system. In order to evaluate the effect of a connected system on overvoltage figure 16 has been included. Figure 16 (*a*) shows how in a particular case $x_q'' = 0.90$, $x_d'' = 0.55$, the overvoltage caused by line-to-line short circuit is reduced by the system tie reactance x_e. All the curves are for the condition of no load and equal voltages on machine and infinite bus. Curve *A* is for short circuit at maximum flux linkage in the shorted phases and approaches the value of equation 1 as the tie reactance approaches infinity. Curve *B* is for short circuit at minimum flux linkage. Curve *C* shows the voltage which would be obtained by the conventional

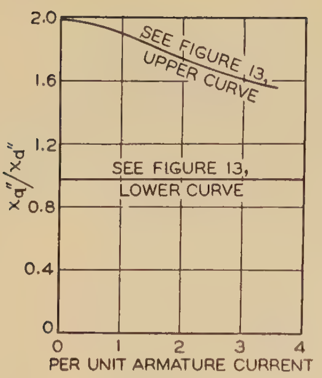


Figure 15. Ratio x_q''/x_d'' determined by single-phase static tests

symmetrical-component calculation. The symmetrical-component method is found to give substantially the fundamental frequency component of voltage. The effect of generator load angle on the maximum overvoltage is indicated by the single point at $x_e = 1.0$.

Figure 16 (*b*) shows more generally the effect of x_q''/x_d'' and the reduction in voltage caused by a reactance tie to an infinite bus. All resistances and capacitances were neglected in calculating the curves of figure 16.

C. Faults Involving Ground

A line-to-line fault was chosen here because the overvoltage depends primarily on the ratio x_q''/x_d'', while for ground faults, the overvoltage is affected also by the method of system grounding. The great majority of faults on power systems involve ground, the line-to-line fault being a less frequent occurrence.

Equivalent circuits for use in determining instantaneous currents and voltages following faults are given in appendix *C* for line-to-ground, line-to-line, and double line-to-ground faults. See figures 18, 19, and 20. From these circuits and either of the methods of calculation given in appendix *B*, overvoltages following faults can be determined.

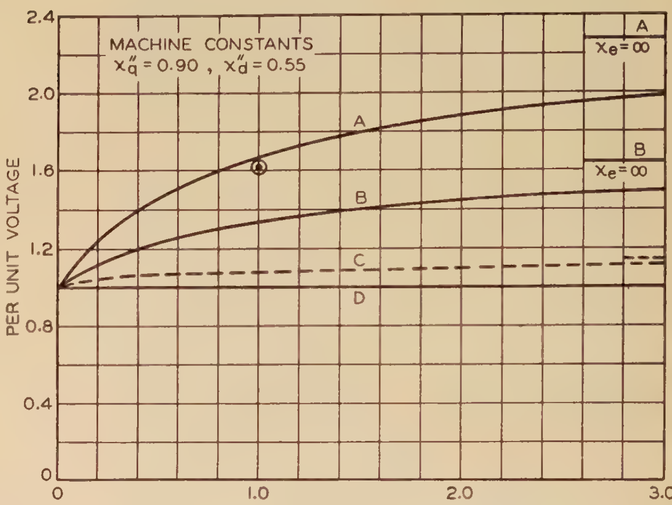
Figure 17 gives resonance regions to third-harmonic currents for the three types of faults when the fault occurs at the terminals of a salient-pole machine connected through impedance to any symmetrical external system in which the positive- and negative-sequence impedance are equal. Resistance is neglected.

Equivalent circuits representing the external system in the positive- and zero-sequence network are shown in figure 17. These circuits consist of a capacitive reactance x_c and an inductive reactance x_e in parallel. In a complex external system, x_{c1}, x_{c0}, x_{1e}, and x_{0e} of the equivalent circuits in general will not be constant for all harmonics.

Figure 17 indicates that with a line-to-ground fault and the assumed ratios of x_{0e}/x_e and x_0/x_2 the capacitance required to cause resonance on a grounded system is high. Even with open lines, a value of x_{c1}/x_2 as low as 5.4 would probably seldom be found in actual systems. For the ungrounded system, the amount of capacitance required for resonance is only about one-fourth to one-fifth as much and the ratio x_{c1}/x_2 lies in a not uncommon region for large systems with long transmission lines.

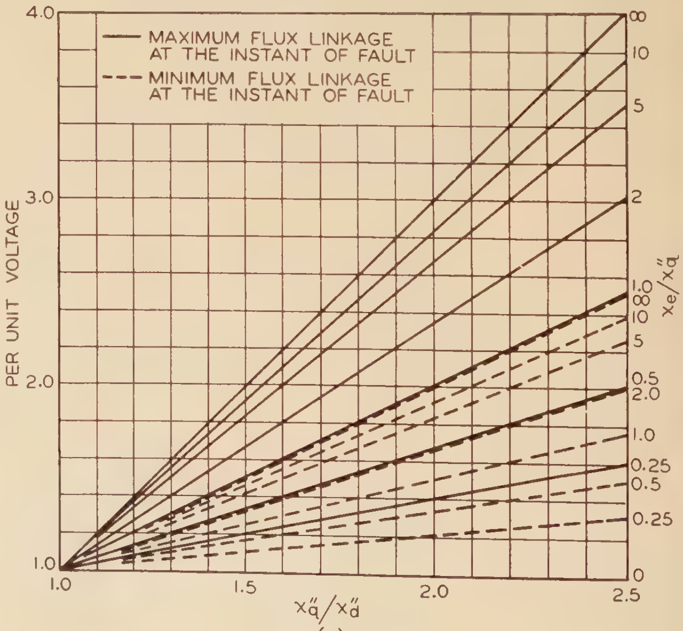
D. Other Functions of Amortisseur Windings

Limitation or reduction of overvoltage is not, of course, the only function of an amortisseur winding and it is necessary to keep the other aspects of amortisseur applications in mind in order properly to determine the best winding for a particular machine. The damping action for rotor oscillations about a steady-state operating angle is determined principally by the amortisseur resistance. A low resistance gives in general the largest damping coefficient for slow oscillations. From the standpoint of



(a)

Curve *A*—No load—fault at maximum flux linkage
Curve *B*—No load—fault at minimum flux linkage
Curve *C*—Symmetrical components—fundamental frequency only
Curve *D*—With $x_q'' = x_d''$
⊙—20-degree load angle—fault at maximum flux linkage



(b)

Figure 16. Line-to-line fault on salient-pole generator—maximum voltage at the point of fault—effect of reactance tie to system

stability the damping action of amortisseur windings is beneficial, but in this case a high-reactance winding which will limit the fault current is desirable. An amortisseur winding will also keep the field voltage on open circuit from reaching dangerous values. These functions do not involve the ratio x_q''/x_d''. However, the recovery voltage on clearing faults has been shown[4] to depend on this ratio.

Nomenclature

x_l = armature leakage reactance
x_{ad} = mutual reactance of armature direct-axis winding with field or amortisseur winding
x_f = field leakage reactance
x_{aq} = mutual reactance of armature and amortisseur quadrature-axis windings
x_d' = direct-axis transient reactance
x_q = quadrature-axis synchronous reactance
r_{kd} = direct-axis amortisseur resistance
r_{kq} = quadrature-axis amortisseur resistance
x_{kd} = direct-axis amortisseur leakage reactance
x_{kq} = quadrature-axis amortisseur leakage reactance
i_d = direct-axis armature current
i_q = quadrature-axis armature current
x_d'' = direct-axis subtransient reactance
x_q'' = quadratue-axis subtransient reactance
x_e = external reactance

$$y = \frac{x_d'' - x_q''}{2}$$

$$x = \frac{x_d'' + x_q''}{2}$$

$$x_{ad}' = \frac{x_{ad}x_f}{x_{ffd}} = x_d' - x_l$$

$x_{ffd} = x_{ad} + x_f$ = field self-reactance

x_c = capacitive reactance

$\alpha_d = \dfrac{r_{kd}}{x_{kd} + x_{ad}'}$ = direct-axis amortisseur decrement factor

$\alpha_q = \dfrac{r_{kq}}{x_{kkq}}$ = quadrature-axis amortisseur decrement factor

$x_{kkq} = x_{aq} + x_{kq}$ = quadrature-axis amortisseur self-reactance

e_a = line-to-neutral armature voltage of the unfaulted phase

$\theta = \theta_0 + t$ = angle between direct axis and phase-a axis

ψ_d', ψ_{d2}' = components of direct-axis armature flux linkage

ψ_q, ψ_{q2} = components of quadrature-axis flux linkage

Subscripts 1, 2, 0, α, β refer to positive, negative, and zero sequence, and to α and β components
Subscript e refers to external circuit

e = voltage
i = current
Z = impedance

Appendix A—Equations for Differential Analyzer

The equations as set up on the differential analyzer were:

$$\psi_d' = -x_d'i_d + \psi_{d2}' \qquad (1a)$$

$$\psi_{d2}' = (x_d' - x_d'')i_d - \alpha_d\int\psi_{d2}'dt \qquad (2a)$$

where

$$\alpha_d = \frac{r_{kd}}{x_{kd} + x_{ad}'}$$

$$x_{ad}' = \frac{x_{ad}x_{fd}}{x_{ffd}}$$

$$\psi_{d20}' = -\left(\frac{x_d' - x_d''}{x_c}\right) - \left(1 - \frac{x_d'}{x_c}\right)\left(\frac{x_{ad}'}{x_{kd} + x_{ad}'}\right)$$

= initial value of ψ_{d2}'

$$\psi_q = -x_qi_q + \psi_{q2} \qquad (3a)$$

$$\psi_q = (x_q - x_q'')i_q - \alpha_q\int\psi_{q2}dt \qquad (4a)$$

where

$$\alpha_q = \frac{r_{kq}}{x_{kkq}}$$

$$\psi_{q20} = 0$$

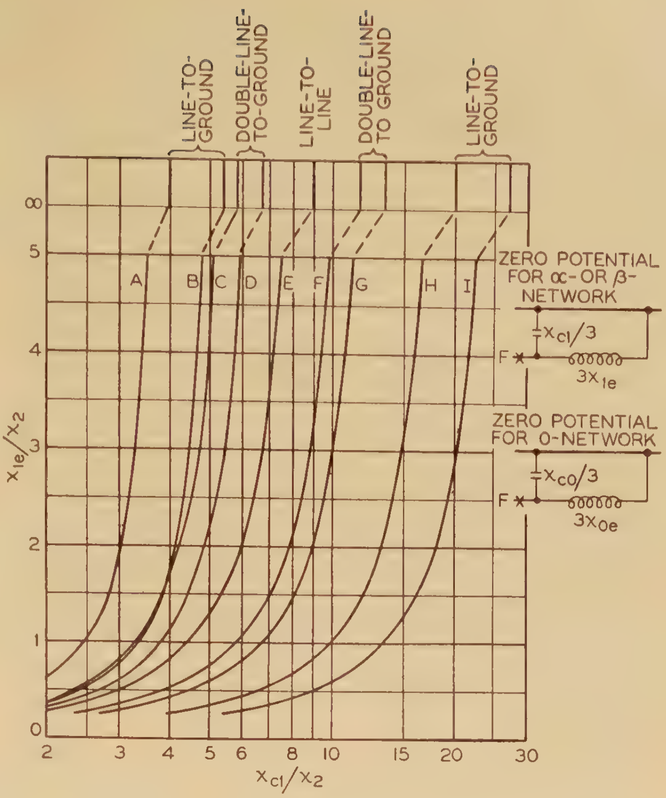


Figure 17. Third-harmonic resonance regions for various types of faults

Curve *A*—Line-to-ground fault, grounded system, $x_0 = x_2/2$; $x_{0e} = x_{1e}$; $C_0 = 0.6\ C_1$
Curve *B*—Line-to-ground fault, grounded system, $x_0 = x_2/2$; $x_{0e} = x_{1e}$; $C_0 = C_1$
Curve *C*—Double line-to-ground fault, grounded system; $x_0 = x_2/2$; $x_{0e} = x_{1e}$; $C_0 = 0.6\ C_1$
Curve *D*—Double line-to-ground fault, grounded system, $x_0 = x_2/2$; $x_{0e} = x_{1e}$; $C_0 = C_1$
Curve *E*—Line-to-line fault
Curve *F*—Double line-to-ground fault, ungrounded system, $C_0 = 0.6\ C_1$
Curve *G*—Double line-to-ground fault, ungrounded system, $C_0 = C_1$
Curve *H*—Line-to-ground fault, ungrounded system, $C_0 = 0.6\ C_1$
Curve *I*—Line-to-ground fault, ungrounded system, $C_0 = C_1$

$$\psi_d' = \int (r_a i_d + \psi_q)dt + \int e_a d(\sin\theta) \tag{5a}$$

$$\psi_q = \int (r_a i_q - \psi_d')dt + \int e_a d\,(\cos\theta) \tag{6a}$$

where

$$i_{d0} = -\frac{1}{x_c}$$

$$\psi_{q0} = 0$$

$$e_{a0} = -\sin\theta_0$$

$$i_{q0} = 0$$

$$\psi'_{d0} = \frac{x_d''}{x_c} + \left(1 - \frac{x_d'}{x_c}\right)\left(\frac{x_{kd}}{x_{kd} + x_{ad}'}\right)$$

$$e_a = \int x_c i_d d(\sin\theta) + \int x_c i_q d(\cos\theta) \tag{7a}$$

It will be noted that these equations are in an integral form similar to those of reference 8. Moreover, the initial conditions are in a simplified form valid only for reasonably small r_a, since for the range of line resistance covered in this investigation the load angle δ of the machine was usually negligible and the terminal (i.e., at the terminals of the capacitance) voltage e_a before the short circuit occurred could consequently be expressed as: $e_{q0} = 1$, $e_{d0} = 0$.

In a few cases it was necessary to take into account the initial value of i_q, which could be found by the formula

$$i_{q0} = \frac{\sin\delta}{x_c} \tag{8a}$$

where[9]

$$\tan\delta = \frac{r_a}{x_c - x_q}$$

Equations 1*a* to 7*a* may be derived from Park's[10] synchronous-machine equations, in exactly the same manner as were the equations of reference 8, and so need not be derived here. It should only be pointed out that in equation 5*a* the expression $e_a d(\sin\theta) = e_a \cos\theta\, dt = e_d\, dt$, and similarly for the similar expressions of equations 6*a* and 7*a*. This substitution was made in order to obtain the most desirable analyzer setup.

With the equations expressed as above, eight integrators are seen to be required. In addition, the two remaining integrators were used to generate the required sinusoidal functions[11] $\sin\theta$, $\cos\theta$, so the setup was entirely self contained and required no operators. Figure 11 shows a schematic diagram of the analyzer connections.

Appendix B—Calculation of Overvoltages

The equations of an ideal synchronous machine with any static terminal impedance under the conditions that (1) all rotor resistances are negligibly small, (2) the external circuit parameters are constants, (3) the external circuit is symmetric about phase *a* of the synchronous machine, and (4) the rotor speed is constant, are most simply and conveniently expressed for the present purpose as:

$$\left.\begin{aligned} e_\alpha &= -[p(x + y\cos 2\theta) + r]\,i_\alpha - py\sin 2\theta\, i_\beta = Z_\alpha(p) i_{\alpha e} \\ e_\beta &= -py\sin 2\theta\, i_\alpha - [p(x - y\cos 2\theta) + r]\,i_\beta = Z_\beta(p) i_{\beta e} \\ e_0 &= -[px_0 + r]\,i_0 = Z_0(p) i_{0e} \end{aligned}\right\} \tag{1b}$$

where

$$\left.\begin{aligned} x &= \frac{1}{2}(x_d'' + x_q'') \\ y &= \frac{1}{2}(x_d'' - x_q'') \end{aligned}\right\} \tag{2b}$$

r = armature circuit resistance

$Z_\alpha(p)$, $Z_\beta(p)$, $Z_0(p)$ = operational impedances of the external connected circuit to the α, β, and 0 components of current, respectively

i_α, i_β, i_0 are components of the stator currents defined in terms of the phase currents by the equations:

$$\left.\begin{aligned} i_\alpha &= \frac{2}{3} i_a - \frac{1}{3} i_b - \frac{1}{3} i_c \\ i_\beta &= \frac{1}{\sqrt{3}} i_b - \frac{1}{\sqrt{3}} i_c \\ i_0 &= \frac{1}{3} i_a + \frac{1}{3} i_b + \frac{1}{3} i_c \end{aligned}\right\} \tag{3b}$$

$i_{\alpha e}$, $i_{\beta e}$, i_{0e} are the similar currents flowing in the external circuit. The currents i_α, i_β may also be expressed in terms of the direct- and quadrature- axis components of current by the equations:

$$\left.\begin{aligned} i_\alpha &= i_d\cos\theta - i_q\sin\theta \\ i_\beta &= i_d\sin\theta + i_q\cos\theta \end{aligned}\right\} \tag{4b}$$

i_α is the component of armature current which produces a field in the axis of phase *a* of the synchronous machine and may be regarded as a current which flows through phase *a* and splits into two equal parts which flow through phases *b* and *c* in parallel. i_β is the component of armature current which produces a field in the common axis of phases *b* and *c* and may be regarded as a current flowing only through phases *b* and *c* in series. e_α, e_β, e_0 are components of armature voltage defined by voltage equations similar to (3*b*) and (4*b*). In the special case of a machine without an amortisseur winding the subtransient reactances x_d'', x_q'' are replaced by x_d', x_q, respectively.

Equations 1*b* are most easily derived from the equations of a synchronous machine (with no external impedance) in terms of direct- and quadrature-axis quantities.[10] These are, for zero rotor resistances,

$$\left.\begin{aligned} e_d &= -(p\,x_d'' + r)\,i_d + x_q'' i_q \\ e_q &= -x_d'' i_d - (px_q'' + r)\,i_q \end{aligned}\right\} \tag{5b}$$

Now if equations 4*b* and the similar voltage equations are applied there are equations 1*b* except for the $Z_\alpha(p)$, $Z_\beta(p)$ terms. It is now evident from a consideration of the circuit and the physical interpretations of i_α, i_β, $i_{\alpha e}$, $i_{\beta e}$, e_α, e_β that if a static network is connected to the machine terminals the complete equations 1*b* are obtained. Moreover, if the network is completely symmetric, there is:

$$Z_\alpha(p) = Z_\beta(p) = Z_1(p) = Z_2(p) \tag{6b}$$

where $Z_1(p)$, $Z_2(p)$ are the positive- and negative-sequence operational impedances of the external circuit.

For a line-to-line fault, as shown in figure 1, there is

$$Z_\alpha(p) = \frac{x_c}{p} \tag{7b}$$

and there are no zero-sequence currents or voltages.

Before the fault let

$$e_a = -\sin(\theta_0 - \phi + t)$$

where ϕ is the load angle. Then, from (3*b*)

$$e_\alpha = -\sin(\theta_0 - \phi + t)$$

$$e_\beta = \cos(\theta_0 - \phi + t)$$

The fault is equivalent to the application of a voltage at the terminals of the machine equal and opposite to e_β. Thus when the voltage $e_\beta = -\cos(\theta_0 + t)$ is applied to equations 1*b*, we obtain the components of current caused by the fault. Further the terminal voltage e_α is given by

$$e_\alpha = \frac{x_c}{p} i_\alpha \tag{8b}$$

and the total resultant is obtained by adding e_α to the voltage existing before short circuit. If the speed is constant the current may be obtained as follows.

Equations 1*b* may be written

$$\left.\begin{aligned}[p(1 + y' \cos 2\theta) + r' + Z_\alpha'(p)]\, xi_\alpha + (py' \sin 2\theta)\, xi_\beta &= 0\\ (py' \sin 2\theta)\, xi_\alpha + [p(1 - y' \cos 2\theta) + r']\, xi_\beta &= \cos(\theta_0 + t)\end{aligned}\right\} \quad (9b)$$

where

$$y' = \frac{y}{x}, \quad r' = \frac{r}{x}, \quad Z' = \frac{Z}{x}$$

It is difficult to obtain a simple finite operational solution to equations 9*b* because of the presence of the periodic time functions in the current coefficients. However a solution may easily be found by expanding the currents in powers of the troublesome coefficient y' about $y' = 0$. We then have

$$\left.\begin{aligned}i_\alpha &= i_{\alpha 0} + i_{\alpha 0}'y' + \frac{i_{\alpha 0}''}{2!}\, y'^2 + \ldots\ldots\\ i_\beta &= i_{\beta 0} + i_{\beta 0}'y' + \frac{i_{\beta 0}''}{2!}\, y'^2 + \ldots\ldots\end{aligned}\right\} (10b)$$

where the primes on the currents indicate differentiation with respect to y' and the subscripts zero indicate evaluation at $y' = 0$.

To obtain $i_{\alpha 0}$, $i_{\beta 0}$ we have merely to let $y' = 0$ in equations 9*b* and then to solve the resulting two independent equations operationally. Next, to obtain $i_{\alpha 0}'$, $i_{\beta 0}'$ we must (1) differentiate (9*b*) with respect to y', (2) let $y' = 0$, (3) substitute for $i_{\alpha 0}$, $i_{\beta 0}$ their values as previously found, (4) obtain the operational solution to the resulting equation. To obtain $i_{\alpha 0}''$, $i_{\beta 0}''$ we proceed in exactly the same way by differentiating again and utilizing the previously found values of $i_{\alpha 0}'$, $i_{\beta 0}'$. For the general coefficients $i_{\alpha 0}^{n'}$, $i_{\beta 0}^{n'}$ of (10*b*) there are the equations,

$$\left.\begin{aligned}&[p + r' + Z_\alpha'(p)]\, i_{\alpha 0}^{(n-1)'} =\\ &\qquad - np\, [(\cos 2\theta)\, i_{\alpha 0}^{(n-1)'} + (\sin 2\theta)\, i_{\beta 0}^{(n-1)'}]\\ &[p + r']\, i_{\beta 0}^{n'} = - np\, [(\sin 2\theta)\, i_{\alpha 0}^{(n-1)'} - (\cos 2\theta)\, i_{\beta 0}^{(n-1)'}]\end{aligned}\right\} (11b)$$

The currents, and consequently the terminal voltage by equation 8*b*, are now determined as infinite series of transient and steady-state terms which, however, converge rapidly because in the usual case y' is much smaller than unity. Figure 10 shows for a particular case a comparison of voltage calculated by the formulas developed above with a curve taken on the differential analyzer and with a step-by-step solution of equations 1*b*. Only the first two terms of (10*b*) were considered in calculating the points of figure 10.

If only the steady-state (as far as armature transients are concerned) voltage is desired the equations are very much simplified since then the currents and voltages appear only as a series of odd-harmonic terms and the operational impedances of equations 1*b* and 11*b* may be replaced by steady-state impedances at the proper frequency. Figure 9 shows a comparison of maximum overvoltages calculated by this simplified method with the overvoltages obtained by the differential analyzer.

A second method of procedure in solving equations 1*b* is to assume that currents and voltages of fundamental frequency can be determined with sufficient accuracy by the method of symmetrical components. It can be applied to systems of any degree of complexity. Since symmetrical components are in general use, the procedure in determining instantaneous currents and voltages following faults will be given in terms of symmetrical components, the α- and β-components being used only to pass from direct and quadrature components to symmetrical components. An advantage of using α- and β-components over positive- and negative-sequence components, is that the relations among the α and β currents and voltages may be expressed by real coefficients.

The following equations give the relations between the positive- and negative-sequence components of currents, voltages, and impedances and the α- and β-components.

$$\left.\begin{aligned}i_\alpha &= i_{a1} + i_{a2}\\ i_\beta &= -j(i_{a1} - i_{a2})\\ e_\alpha &= e_{a1} + e_{a2}\\ e_\beta &= -j(e_{a1} - e_{a2})\\ i_{a1} &= \frac{1}{2}(i_\alpha + ji_\beta)\\ i_{a2} &= \frac{1}{2}(i_\alpha - ji_\beta)\\ e_{a1} &= \frac{1}{2}(e_\alpha + je_\beta)\\ e_{a2} &= \frac{1}{2}(e_\alpha - je_\beta)\\ Z_\beta &= \frac{1}{2}(Z_1 + Z_2)\\ Z_\alpha &= 2\frac{Z_1Z_2}{Z_1 + Z_2} \cong \frac{1}{2}(Z_1 + Z_2)\end{aligned}\right\} \quad (12b)$$

Reference Vector

In the method of symmetrical components, sinusoidal voltages and currents of fundamental frequency are represented by vectors referred to some particular vector as reference. Thus, if the voltage e_a of phase *a* at some specified point leads the reference vector by an angle α, it is written

$$e_a = |\,e_a\,|\,\underline{/\alpha} = E_a\,\underline{/\alpha}$$

To express e_a as a function of time, let the fundamental frequency component of e_a be written

$$e_{1a} = -E_{1a} \sin(\theta + \alpha_1) = E_{1a}\underline{/\theta + \alpha_1}$$

and the *n*th harmonic component of e_a

$$e_{na} = -E_{na} \sin(n\theta + \alpha_n) = E_{na}\underline{/n\theta + \alpha_n}$$

where θ is the position of the axis of the rotor of a specified machine in electrical degrees measured from the axis of phase *a*.

The following expressions for instantaneous values of currents and voltages of any frequency will be used interchangeably,

$$-V \sin(n\theta \pm \alpha) = V\,\underline{/n\theta \pm \alpha}$$

$$V \cos(n\theta \pm \alpha) = -jV\,\underline{/n\theta \pm \alpha} = V\,\underline{/n\theta \pm \alpha - 90°}$$

$$\pm jV \sin(n\theta + \alpha) = V \sin(n\theta + \alpha \pm 90°) = \pm V \cos(n\theta + \alpha)$$

$$\pm jV \cos(n\theta + \alpha) = V \cos(n\theta + \alpha \pm 90°) = \mp V \sin(n\theta + \alpha)$$

Let

$$\left.\begin{aligned}i_{na1} &= \text{positive-sequence } n\text{th harmonic current}\\ &= -jI_{na1}\,\underline{/n\theta + \alpha_{n1}} = I_{na1} \cos(n\theta + \alpha_{n1})\\ i_{na2} &= \text{negative sequence } n\text{th harmonic current}\\ &= -jI_{na2}\,\underline{/n\theta + \alpha_{n2}} = I_{na2} \cos(n\theta + \alpha_{n2})\end{aligned}\right\} (13b)$$

where α_{n1} and α_{n2} are determined by the system impedances, type of fault, and load angle.

Generated Voltages

When $x_q'' = x_d''$, currents and voltages following faults will in the general case have a fundamental-frequency term, one or more natural-frequency terms, and a d-c term. These can be determined by

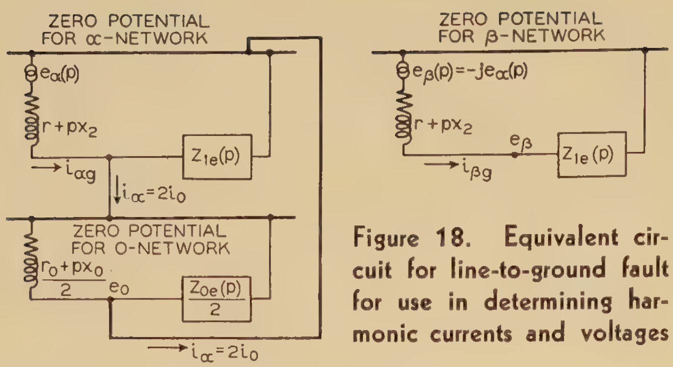


Figure 18. Equivalent circuit for line-to-ground fault for use in determining harmonic currents and voltages

applying a voltage at the fault equal and opposite to that which existed there before the fault and adding resulting changes in currents and voltages to initial values. When $x_q'' \neq x_d''$, additional voltages are generated. From (1*b*) the voltages generated by sinusoidal currents i_α and i_β of any frequency are

$$\left.\begin{aligned} e_\alpha &= -py(\cos 2\theta i_\alpha + \sin 2\theta i_\beta) \\ e_\beta &= -py(\sin 2\theta i_\alpha - \cos 2\theta i_\beta) \end{aligned}\right\} \quad \textbf{(14b)}$$

Replacing i_α and i_β in (14*b*) by their positive- and negative-sequence values from (12*b*) and substituting for them the expressions in (13*b*), positive- and negative-sequence voltages generated in a given machine can be determined as follows:

$$\left.\begin{aligned} e_\alpha = {} & -py[I_{na1}\{\cos 2\theta \cos(n\theta+\alpha_{n1}) + \\ & \sin 2\theta \sin(n\theta+\alpha_{n1})\} + I_{na2}\{\cos 2\theta \cos(n\theta+\alpha_{n2}) - \\ & \qquad \sin 2\theta \sin(n\theta+\alpha_{n2})\}] \\ = {} & -py[I_{na1}\cos\{(n-2)\theta+\alpha_{n1}\} + \\ & \qquad I_{na2}\cos\{(n+2)\theta+\alpha_{n2}\}] \\ = {} & (n-2)yI_{na1}\sin\{(n-2)\theta+\alpha_{n1}\} + \\ & \qquad (n+2)yI_{na2}\sin\{(n+2)\theta+\alpha_{n2}\} \\ e_\beta = {} & -py[I_{na1}\{\sin 2\theta \cos(n\theta+\alpha_{n1}) - \\ & \cos 2\theta \sin(n\theta+\alpha_{n1})\} + \\ & I_{na2}\{\sin 2\theta \cos(n\theta+\alpha_{n2}) + \cos 2\theta \sin(n\theta+\alpha_{n2})\}] \\ = {} & -py[-I_{na1}\sin\{(n-2)\theta+\alpha_{n1}\} + \\ & \qquad I_{na2}\sin\{(n+2)\theta+\alpha_{n2}\}] \\ = {} & (n-2)yI_{na1}\cos\{(n-2)\theta+\alpha_{n1}\} - \\ & \qquad (n+2)yI_{na2}\cos\{(n+2)\theta+\alpha_{n2}\} \end{aligned}\right\} \quad \textbf{(15b)}$$

If $n \geqq 2$

$$\begin{aligned} je_\beta = {} & -(n-2)yI_{na1}\sin[(n-2)\theta+\alpha_{n1}] + \\ & \qquad (n+2)y\,I_{na2}\sin[(n+2)\theta+\alpha_{n2}] \end{aligned} \quad \textbf{(16b)}$$

$$\begin{aligned} e_{a1} &= (n+2)yI_{na2}\sin[(n+2)\theta+\alpha_{n2}] \\ &= -(n+2)y\,I_{na2}\underline{/(n+2)\theta+\alpha_{n2}} = \\ &\qquad (n+2)\,y\underline{/2\theta-90^\circ}\,i_{na2} \end{aligned} \quad \textbf{(17b)}$$

$$\begin{aligned} e_{a2} &= (n-2)yI_{na1}\sin[(n-2)\theta+\alpha_{n1}] \\ &= -(n-2)yI_{na1}\underline{/(n-2)\theta+\alpha_{n1}} = \\ &\qquad (n-2)y\underline{/-2\theta-90^\circ}\,i_{na1} \end{aligned} \quad \textbf{(18b)}$$

If $n = 1$

$$\begin{aligned} e_{a1} &= yI_{na1}\sin(\theta-\alpha_{n1}) \\ &= -yI_{1a1}\underline{/\theta-\alpha_{11}} = y\,\underline{/-2\alpha_{11}-90^\circ}\,i_{1a1} \\ e_{a2} &= 0 \end{aligned} \quad \textbf{(19b)}$$

From (17*b*), (18*b*), (19*b*), positive- and negative-sequence voltages generated by harmonic current without decrements can be determined.

Steady State

Since zero rotor resistance has been assumed in the direct and quadrature axes, there will be no field decrements and fundamental-frequency and odd-harmonic terms of currents and voltages will have no decrements. Natural-frequency and even harmonic terms will disappear in the steady state.

Table II gives the positive- and negative-sequence odd-harmonic voltages generated by positive- and negative-sequence odd-harmonic currents.

Procedure in Determining Steady-State Values of Currents and Voltages Following Faults

Assuming zero resistance in the field for machines without amortisseur windings and also in the amortisseur for those with amortisseur windings, the procedure for determining currents and voltages in the steady state following faults is as follows:

1. Calculate currents and voltages of fundamental frequency in the system by means of symmetrical components. Since it has been assumed that fundamental-frequency currents and voltages are determined with sufficient accuracy by this method, voltages of fundamental frequency generated in machines in which $x_d'' \neq x_q''$ will be neglected.

2. From the negative-sequence current flowing in machines in which $x_d'' \neq x_q''$, determine the third-harmonic positive-sequence generated voltages from table II.

3. From third-harmonic positive-sequence generated voltages determine by symmetrical components the third-harmonic voltages and currents in the systems, assuming positive and negative impedance of the synchronous machines to third-harmonic currents to be $3x_2$. x_2 may differ slightly from the fundamental-frequency value.

4. From the negative sequence third-harmonic currents flowing in machines in which $x_d'' \neq x_q''$, determine from table II the fifth-harmonic positive-sequence generated voltages.

Proceeding in this manner, odd-harmonic currents and voltages can be determined at any point of the system.

It is also possible to calculate the transient voltage caused by odd harmonic currents and, by using the natural frequency and even harmonic currents in equations (14*b*) to calculate the generated transient voltages and from them in turn the resulting terminal overvoltage.

Appendix C—Equivalent Circuits for Various Types of Faults

Let i_a, i_b, and i_c be phase currents flowing into the fault; $Z_0(p)$ the zero-sequence impedance viewed from the fault; e_a, e_b, and e_c the phase-to-ground voltages at the fault, and e_α, e_β, and e_0 their α-, β-, and 0-components, respectively.

Line-to-Ground Fault (Phase a)

Conditions at the fault are:

$$i_b = i_c = 0;\ e_a = 0$$

From (3*b*)

$$i_\beta = 0;\ i_\alpha = 2i_0;\ e_\alpha = -e_0$$

Table II. Positive- and Negative-Sequence* Odd-Harmonic Generated Voltages

Positive-Sequence Odd-Harmonic Voltages Generated in Machines by Negative-Sequence Currents

$$\begin{aligned} e_{3a1} &= 3yI_{1a2}\sin(3\theta+\alpha_{12}) = -3yI_{1a2}\underline{/3\theta+\alpha_2} = 3y\underline{/2\theta-90^\circ}\,i_{1a2} \\ e_{5a1} &= 5yI_{3a2}\sin(5\theta+\alpha_{32}) = -5yI_{3a2}\underline{/5\theta+\alpha_{23}} = 5y\underline{/2\theta-90^\circ}\,i_{3a2} \\ e_{8a1} &= 7yI_{5a2}\sin(7\theta+\alpha_{52}) = -7yI_{5a2}\underline{/7\theta+\alpha_{25}} = 7y\underline{/2\theta-90^\circ}\,i_{5a2} \\ e_{9a1} &= 9yI_{7a2}\sin(9\theta+\alpha_{72}) = -9yI_{7a2}\underline{/9\theta+\alpha_{27}} = 9y\underline{/2\theta-90^\circ}\,i_{2a2} \end{aligned}$$

Negative-Sequence Odd-Harmonic Voltages Generated in Machines by Positive Sequence Currents

$$\begin{aligned} e_{1a2} &= yI_{3a1}\sin(\theta+\alpha_{31}) = -yI_{3a1}\underline{/\theta+\alpha_{31}} = y\underline{/-2\theta-90^\circ}\,i_{3a1} \\ e_{3a2} &= 3yI_{5a1}\sin(3\theta+\alpha_{51}) = -3yI_{5a1}\underline{/3\theta+\alpha_{51}} = 3y\underline{/-2\theta-90^\circ}\,i_{5a1} \\ e_{7a2} &= 5yI_{7a1}\sin(5\theta+\alpha_{71}) = -5yI_{7a1}\underline{/5\theta+\alpha_{71}} = 5y\underline{/-2\theta-90^\circ}\,i_{7a1} \\ e_{7a2} &= 7yI_{9a1}\sin(7\theta+\alpha_{91}) = -7yI_{9a1}\underline{/7\theta+\alpha_{91}} = 7y\underline{/-2\theta-90^\circ}\,i_{9a1} \end{aligned}$$

*α and β voltages when required can be obtained from table II and (12*b*).

It follows that

$$-e_0 = Z_0(p)i_0 = \frac{Z_0(p)}{2}\,i_\alpha = e_\alpha \qquad (1c)$$

From (1*c*) the equivalent circuit to replace the fault in the α-network is $Z_0(p)/2$. When $x_d'' = x_q''$, the β-network is not involved, e_β is not changed by the fault, and e_α and e_0 have only fundamental- and natural-frequency terms. In machines in which $x_d'' \neq x_q''$, fundamental-, harmonic- and other frequency voltages are generated (see appendix *B*) which affect e_α, e_β, and e_0.

At the fault, since $e_\alpha = -e_0$, e_a, e_b, and e_c are:

$$\left.\begin{aligned}
e_a &= e_\alpha + e_0 = 0\\
e_b &= -\frac{1}{2}\,e_\alpha + e_0 - \frac{\sqrt{3}}{2}\,e_\beta = \frac{3}{2}\,e_0 - \\
&\qquad \frac{\sqrt{3}}{2}\,e_\beta = -\frac{3}{2}\,e_\alpha - \frac{\sqrt{3}}{2}\,e_\beta\\
e_c &= -\frac{1}{2}\,e_\alpha + e_0 + \frac{\sqrt{3}}{2}\,e_\beta = \frac{3}{2}\,e_0 + \\
&\qquad \frac{\sqrt{3}}{2}\,e_\beta = -\frac{3}{2}\,e_\alpha + \frac{\sqrt{3}}{2}\,e_\beta
\end{aligned}\right\} \qquad (2c)$$

Line-to-Line Fault (Phases b and c)

Conditions at the fault are:

$$i_b = -i_c;\; i_a = 0;\; e_b = e_c$$

From (3*b*)

$$i_\alpha = i_0 = 0;\; e_\beta = 0$$

For a system symmetrical before the fault, the zero-sequence network is not involved. The β-network is shorted at the point of fault. The α-network is unaffected when $x_d'' = x_q''$, but when $x_d'' \neq x_q''$ voltages are generated in the machines which affect e_α. (see appendix *B*). At the fault,

$$\left.\begin{aligned}
e_a &= e_\alpha\\
e_b &= e_c = -\frac{1}{2}\,e_\alpha
\end{aligned}\right\} \qquad (3c)$$

Double Line-to-Ground Fault (Phases b and c)

Conditions at the fault are:

$$i_a = 0;\; e_b = e_c = 0$$

From (3*b*)

$$e_\beta = 0;\; e_\alpha = 2e_0;\; i_\alpha = -i_0$$

It follows that

$$2e_0 = -2Z_0(p)i_0 = 2Z_0(p)i_\alpha = e_\alpha \qquad (4c)$$

The equivalent circuit to replace the fault in the α-network is therefore $2Z_0(p)$. The β-network is shorted at the point of fault. When $x_d'' = x_q''$, there is no mutual coupling between the α- and β-networks, but when $x_d'' \neq x_q''$, voltages are generated in the machines which affect e_α and e_0. (See appendix *B*.)

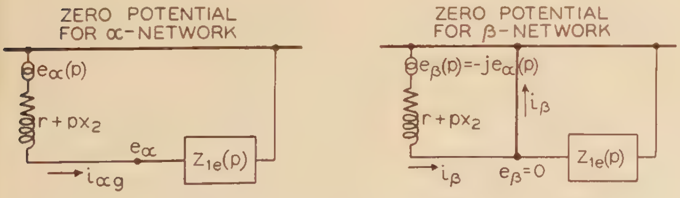


Figure 19. Equivalent circuit for line-to-line fault for use in determining harmonic currents and voltages

At the fault,

$$\left.\begin{aligned}
e_a &= e_\alpha + e_0 = 3e_0 = \frac{3}{2}\,e_\alpha\\
e_b &= e_c = 0
\end{aligned}\right\} \qquad (5c)$$

In figures 18, 19, 20 are shown the equivalent circuits for line-to-ground, line-to-line, and double line-to-ground faults at the terminals of a synchronous generator with series impedance connected to any symmetrical external system in which the positive- and negative-sequence impedances are equal. $Z_{1e}(p)$ and $Z_{0e}(p)$ are the operational expressions for the positive- and zero-sequence impedances of the external system. $r_0 + px_0$ is the zero-sequence impedance of the generator. The positive- and negative-sequence impedances of the generator to currents of frequencies other than fundamental is approximately $r + px_2$ except for very high frequencies. This is also the α and β impedances to them.

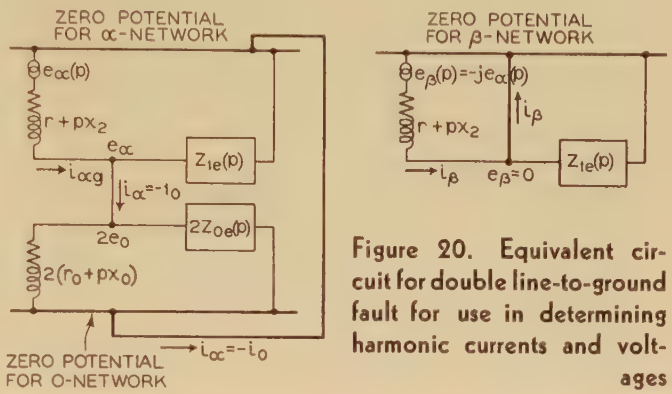


Figure 20. Equivalent circuit for double line-to-ground fault for use in determining harmonic currents and voltages

Except for voltages of fundamental frequency which are determined by the method of symmetrical components, the equivalent circuits of figures 18, 19, 20 can be used to determine all other components of current and voltage. The principal natural-frequency terms are calculated by the application of a voltage at the point of fault equal and opposite to the initial steady-state voltage. The point of application of voltages generated when $x_d'' \neq x_q''$ is taken in the machine.

Resonance to Harmonics

Harmonic voltages are generated in machines in which $x_d'' \neq x_q''$. The external impedance which will cause resonance for various types of faults can be determined from the equivalent circuits as follows:

From equation 2*c* and figure 18, resonance for a line-to-ground fault can occur either in the unfaulted β-circuit or in the α-circuit. For resonance to the *n*th harmonic in the β-circuit there is the equation:

$$nx_2 = \text{negative reactance component of } Z_{1e}(p)$$

For resonance in the α-circuit,

$$nx_2 = \text{negative reactance component of } \frac{r_0 + px_0}{2},\ \frac{Z_{0e}(p)}{2},\ \text{and } Z_{1e}(p)$$

in parallel.

It is thus possible to have resonance to one harmonic in the α-circuit and to another in the β-circuit.

For the line-to-line and the double line-to-ground faults resonance can only occur in the α-circuit. For the line-to-line fault it will occur when

$$nx_2 = \text{negative reactance component of } Z_{1e}(p)$$

For the double line-to-ground fault when

nx_2 = negative reactance component of $2(r_0 + px_0)$, $2Z_{0e}(p)$, and $Z_{1e}(p)$ in parallel.

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Discussion

D. E. Brainard (General Electric Company, Schenectady, N. Y.): The authors have pointed out that they controlled the point on the voltage wave at which the short circuits were applied. By choosing the point of maximum linkages they obtained the maximum possible overvoltage. When the usual random shots must be accepted, it is necessary to estimate the maximum overvoltage for a given machine by observing the point on the cycle at which each value of overvoltage occurs.

This procedure was applied in the case of a 26-pole, 1,250-kva 600-volt generator having a copper amortisseur winding without connected end rings. With the machine operating at 0.33, 0.66, and 1.0 per unit voltage, single phase, line-to-line, sudden short circuits were applied. The values of the ratio of the maximum voltage obtained on the open phase to the voltage before the short are plotted in figure 1. These voltages were measured by an oscillograph both from open line to neutral and from open line to shorted lines. The angle was determined from the oscillogram of the voltage between the two terminals which were shorted.

A curve drawn through the test points gives a maximum ratio for the line-to-neutral case of 1.68 for the short from 0.33 voltage. The short-circuit current for this case is of the order of rated current for which condition static tests show a ratio of $x_q''/x_d'' = 1.33$. The formula given in the paper gives a maximum voltage ratio of 1.66 with which the test is in substantial agreement. It is to be noted, however, that the line-to-line-voltage ratio reaches a maximum of only 1.5 for the same conditions.

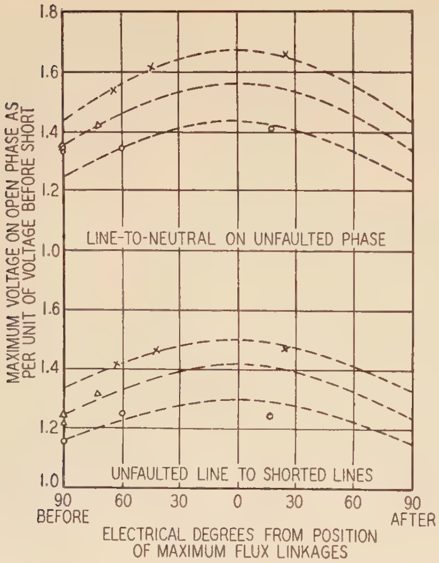


Figure 1. Open-phase voltages following single-phase line-to-line short circuits (as a function of linkages in shorted phase when shorted)

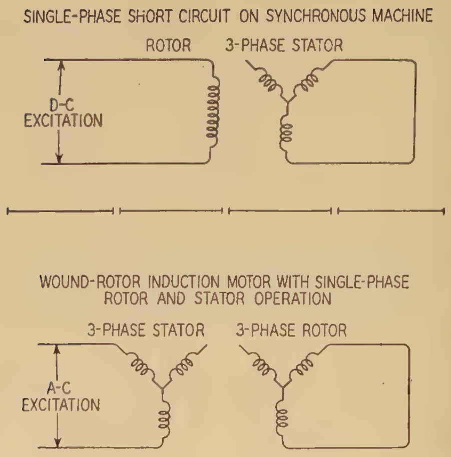
Tests on 26-pole 1,250-kva 600-volt machine having copper amortisseur winding without connected end rings

$x_q''/x_d'' = 1.33$ by static test at 1.0 per unit current

Per unit voltage before short as follows:

x = 0.33 Δ = 0.66 0 = 1.00

Figure 2



SINGLE-PHASE SHORT CIRCUIT ON SYNCHRONOUS MACHINE
ROTOR
3-PHASE STATOR
D-C EXCITATION
WOUND-ROTOR INDUCTION MOTOR WITH SINGLE-PHASE ROTOR AND STATOR OPERATION
3-PHASE STATOR
3-PHASE ROTOR
A-C EXCITATION

J. H. Fortenbach (nonmember; General Electric Company, Schenectady, N. Y.): The problem of single-phase short circuit on a synchronous machine is analogous to the problem of a wound-rotor induction motor when operating with single-phase excitation on the stator and with only one phase short-circuited on the rotor. The chief differences are that the induction motor is a round-rotor machine and the excitation is alternating current rather than direct current. Figure 2 illustrates the analogy.

We have known for many years that operation of a wound-rotor induction motor in such a manner produced abnormal voltages across the open phases. From the various tests which were made in the past, it was found that under these conditions the voltage across the open phase of either the rotor or stator might be in the order of ten times normal.

The most recent tests which we made on a three-phase wound-rotor induction motor with single-phase rotor and stator were taken in 1931. These were made on an 8-pole 15-horsepower 900-rpm 220-volt three-phase 60-cycle motor. The motor, at first unexcited, was driven and held at a constant speed. Single-phase normal voltage was then suddenly applied across two stator lines. The oscillogram (figure 3) shows a typical result for the case when the machine was driven at 900 rpm.

By assuming that the mutual inductance between a stator and a rotor phase is proportional to the cosine of their relative angular displacement and that the rotor and stator resistances are equal to zero, we were able to calculate (for the steady state) the voltages and currents shown by the oscillogram.

The method used was to set up in operational form, the self and mutual induced voltages in each phase of the rotor and stator. The six equations resulting were solved for the steady state condition. The calculated results for one of the open stator and one of the open rotor voltages are shown by figure 4.

The circled points are the tested values taken from the oscillogram.

Figure 3

A—Open-stator voltage; one centimeter = 328 volts

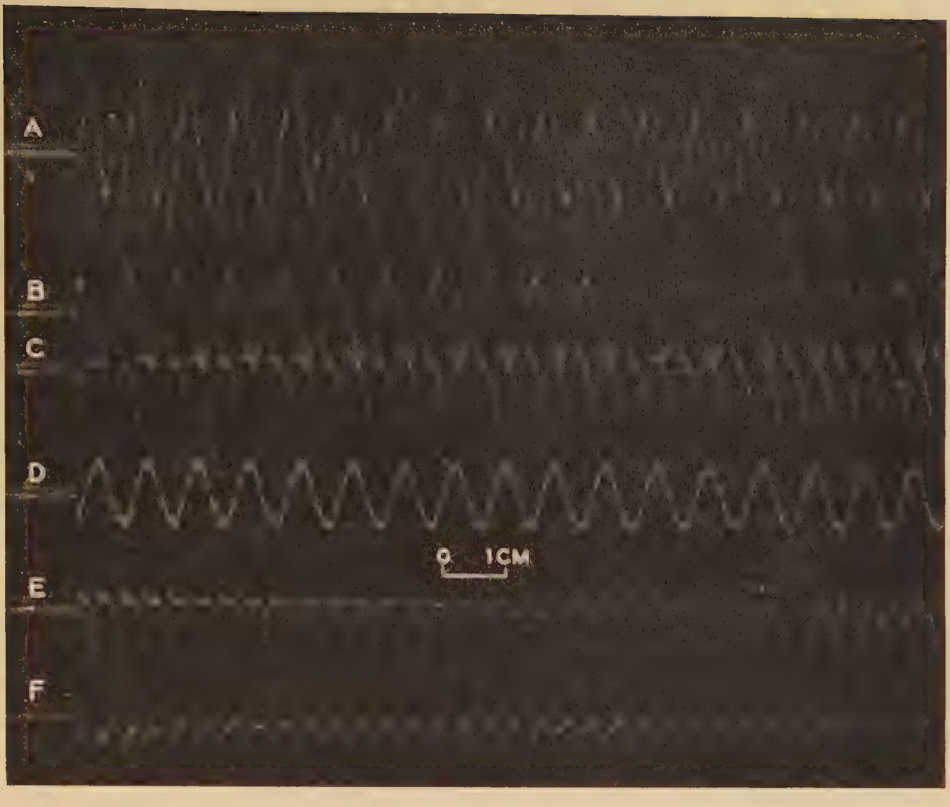
B—Open-stator voltage; one centimeter = 518 volts

C—Rotor current; one centimeter = 115 amperes

D—Applied stator voltage; one centimeter = 622 volts

E—Open-rotor voltage; one centimeter = 516 volts

F—Open-rotor voltage; one centimeter = 258 volts



E. M. Hunter (General Electric Company, Schenectady, N. Y.): This study of overvoltages caused by unbalanced short circuits described by the authors is illuminating when viewed in the light of operating experiences reported on ungrounded-neutral systems. The disturbances resulting from overvoltages during ground faults on ungrounded neutral systems have been described frequently in the technical press. They have been attributed to "arcing grounds." Numerous attempts have been made to reproduce "arcing grounds" during staged tests with little success, which has led to the suspicion that the overvoltages that have occurred should be explained in some other way.

The authors' figure 17 shows the areas in which overvoltages may occur. A study of this figure indicates that the chances of obtaining the overvoltages described are greater on the ungrounded-neutral system. It would appear that at least some of the overvoltages previously attributed to "arcing grounds" have actually resulted from the phenomena described in this paper.

The authors have suggested that to reduce the overvoltages, the generators be equipped with amortisseur windings. The ground

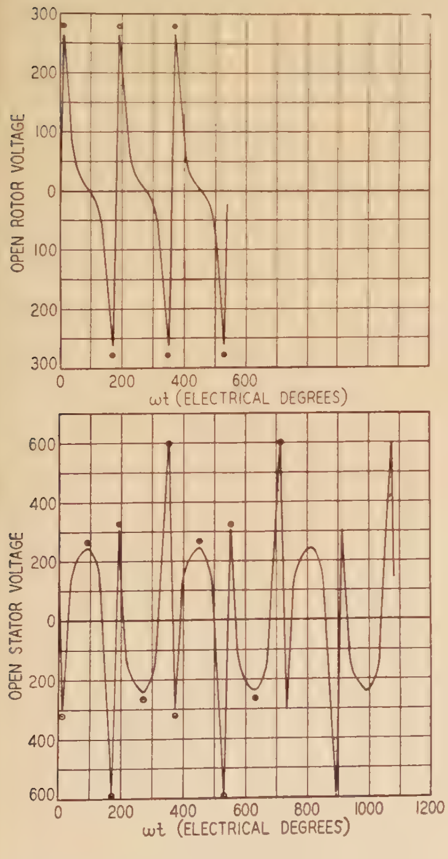


Figure 4

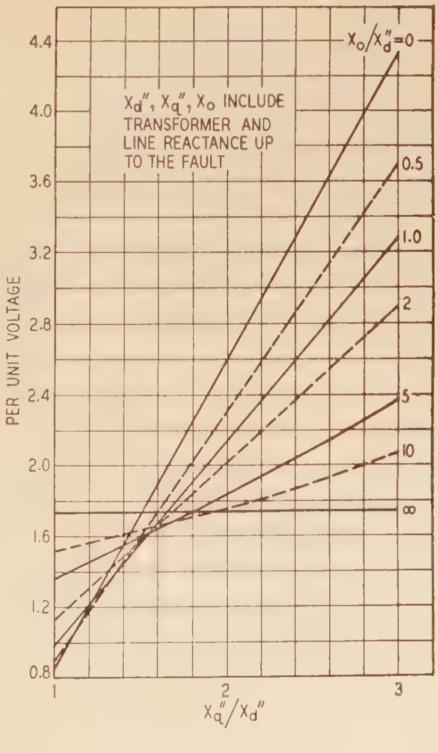


Figure 5. Line-to-ground fault—maximum voltage of the unfaulted phases in per unit of crest voltage before the fault. Constant rotor flux linkages—resistance and capacitance neglected—maximum flux linkages

fault neutralizer (Petersen coil) is also effective in reducing them. On a system with a neutralizer the zero-sequence impedance is infinite. Accordingly, during line-to-ground faults, there is no flow of positive or negative fault current. When the neutralizers are located on the system, there is little negative-sequence current flowing to produce the excitation necessary for the overvoltages. Referring again to the authors' figure 17, curves *F*, *G*, *H*, and *I* represent the areas where resonance occurs and overvoltages may be serious for single and double line-to-ground faults on ungrounded neutral systems. These areas are eliminated with ground-fault neutralizers on the system.

Edith Clarke, C. N. Weygandt and **C. Concordia:** Mr. Brainard's tests illustrate the effect of closing angle and show that in order to obtain consistent results, control of this angle is essential. He also finds that the ratio of line-to-line voltage after the fault to that before the fault is smaller than the corresponding line-to-neutral voltage ratio. In the paper it is shown that theoretically the relation is: (line-to-line voltage ratio) = 0.866 (line-to-neutral voltage ratio).

The results presented by Mr. Fortenbach are particularly interesting since they show such an excellent theoretical check of the observed steady-state voltage wave and since they demonstrate the essential similarity of synchronous and induction machines as far as these overvoltages are concerned.

As brought out in the paper, a line-to-line fault was studied in detail because it may result in the highest voltages and because it is the type most affected by changes in x_q''/x_d''. To show the effect of x_q''/x_d'' on voltages arising from line-to-ground faults without capacitance, figure 5 of this closure has been included. The curves of figure 5 show that for small x_q''/x_d'' the overvoltage at the fault increases with increasing x_0, while for large x_q''/x_d'' the situation is reversed and the overvoltage decreases with increasing x_0. It has been pointed out by Mr. Hunter that the effect of a ground fault neutralizer is to make $x_0 = \infty$, so that voltages at the fault would then be practically limited to the value shown in the figure for $x_0 = \infty$.

For the case studied, the open phase voltages are given by:

$$e_b = -\frac{3}{2}e_\alpha + \frac{\sqrt{3}}{2}[e_\beta + \cos(\theta - \alpha)]$$

$$e_c = -\frac{3}{2}e_\alpha - \frac{\sqrt{3}}{2}[e_\beta + \cos(\theta - \alpha)]$$

where

$$e_\alpha = -x_0 \frac{[x_0 + 2x + 2y\cos 2\theta]\sin\theta - 4y\sin 2\theta(\cos\theta - \cos\theta_0)}{[x_0 + 2x + 2y\cos 2\theta]^2}$$

$$e_\beta = 2y \times \frac{(x_0+2x+2y\cos 2\theta)\sin\theta\sin 2\theta - [4y + 2(x_0+2x)\cos 2\theta](\cos\theta - \cos\theta_0)}{[x_0 + 2x + 2y\cos 2\theta]^2}$$

Resonant Nonlinear Control Circuits

By WILLIAM T. THOMSON
ASSOCIATE AIEE

Synopsis: The resonant type of nonlinear circuit containing a resistance, a condenser, and a saturable-core reactor is finding a number of applications in the various engineering fields,[1] and an analytical treatment has here been developed to add to the understanding of the behavior of such circuits. Certain features of the superposition of a d-c magnetizing force on the reactor are discussed. A method of increasing the sensitivity of this d-c controlled circuit, with a mathematical analysis for the criteria of stability and amplification is given. Finally, a specific application of the circuits discussed to a sensitive and stable power controlling device is described.

THE GENERAL characteristics of the resonant nonlinear circuit have been known for some time.[2] However, in order to determine specifically the behavior of such circuits, an analytical treatment is necessary. With such an analysis it is possible to calculate the critical resistance, the critical voltage and the critical current, and a better understanding of such circuits is gained.

The Series Circuit

For the general characteristics of the nonlinear circuit, the reader is referred to the paper on nonlinear circuits by C. G. Suits.[3] For orientation purposes, however, some of the properties of the series nonlinear circuit will be briefly reviewed. Figure 1 illustrates the typical volt-ampere relation of such circuits. The observations to be noted here are:

1. Upon reaching a certain critical voltage, the current takes an abrupt rise.
2. The steepness of this rise in the critical region is some function of the resistance.
3. If this resistance is reduced to a value less than the critical resistance, the circuit becomes unstable in the critical region and displays a hysteresis effect. In this unstable region, the slope dE/dI of the curve becomes negative. See figure 4.
4. The magnitude of the current jump is some function of the condenser size.

The peculiar volt-ampere relation found in such circuits is due to the joint action of saturation of the iron and the partial resonance of the circuit. Figure 2 is an oscillogram illustrating the cumulative action of the current jump in the unstable region.

With these points in mind, the problem will be treated analytically. Referring to the unstable curve of figure 1, there exist two points on the curve where $dE/dI = 0$. Since with a critical resistance in the circuit these two points merge into one, the value of the critical resistance can be obtained by equating the two expressions for the current when $dE/dI = 0$.

Unfortunately very little is known of the nonlinear differential equation encountered for such circuits, and therefore one must resort to the use of an equivalent sine wave and treat the problem vectorially. With such a method, it is obvious that the reactance and the apparent resistance of the reactor must be expressed in terms of the effective current. This is readily accomplished by the following vector relation:

$$X_L = \frac{1}{I}\sqrt{E_L^2 - \left(\frac{W}{I}\right)^2} \qquad (1)$$

$$R_L = \frac{W}{I^2} \qquad (2)$$

where

X_L = effective reactance of the reactor
R_L = apparent resistance of the reactor
E_L = effective voltage across the reactor
W = watts consumed by the reactor
I = effective current

In plotting X_L and R_L against the current, the curves

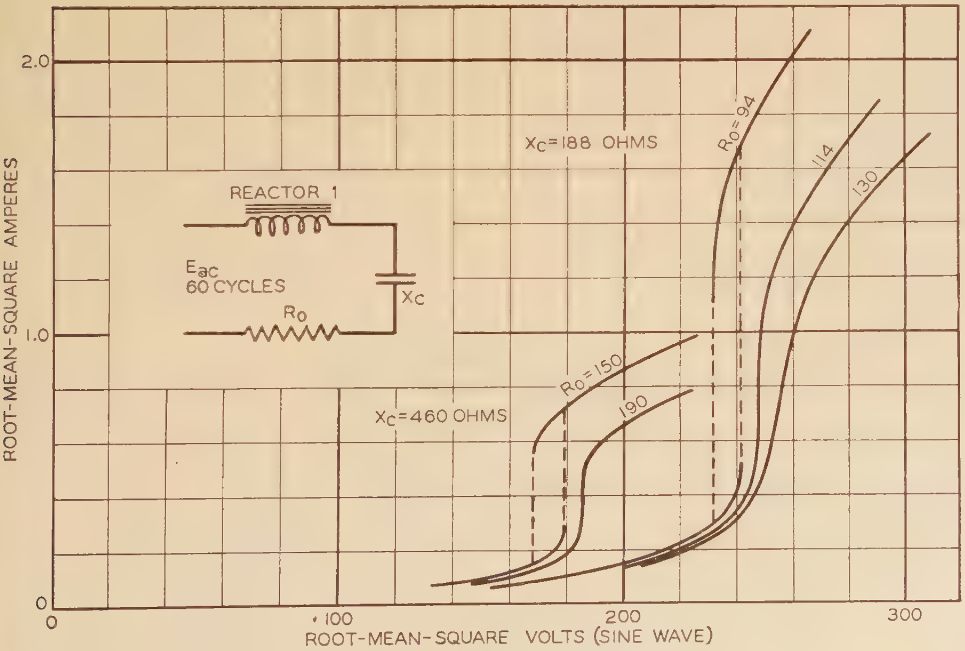


Figure 1. Characteristics of the series circuit

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[1] For all numbered references, see list at end of paper.

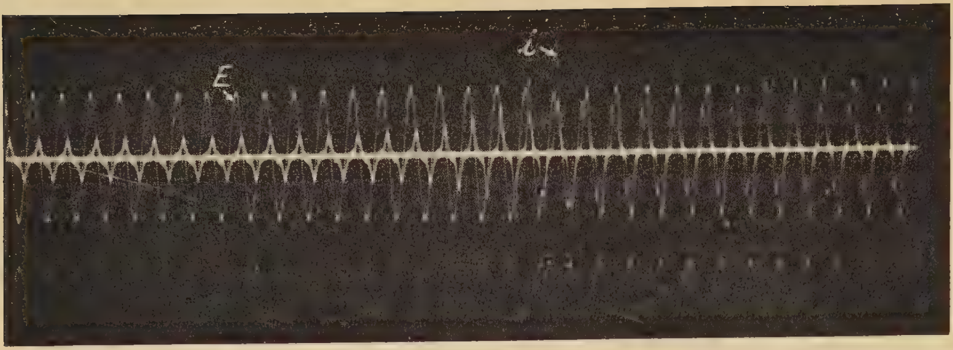


Figure 2. Current jump at critical voltage

appear as in figure 3. Since the critical condition always occurs on the negative-slope portion of the reactance curve, it is only necessary to fit an equation over this region. The equation best fitting these curves is a rectangular hyperbola with displaced axis, and R_L and X_L can be expressed as follows:

$$R_L = \frac{A}{\alpha + I} + K_1 \tag{3}$$

$$X_L = \frac{B}{\beta + I} + K_2 \tag{4}$$

where A, α, B, β, K_1 and K_2 are constants of the reactor. The constants are calculated by taking three points covering the desired interval of the curve.

Using these expressions in the voltage equation;

$$E = I\sqrt{R^2 + X^2} \tag{5}$$

where

$R = R_0 + R_L$, the sum of the series and the apparent resistance of the reactor

$X = X_L - X_c$, the difference in the reactive impedances,

equation 5 can be differentiated with respect to the current and set equal to zero.

$$R\left(R + I\frac{dR_L}{dI}\right) + X\left(X + I\frac{dX_L}{dI}\right) = 0 \tag{6}$$

The difficulty with this last equation when the expressions for X_L and R_L are substituted is that it is not solvable mathematically. However, by plotting equation 6 for various values of resistance it is found that the current for the maximum negative dE/dI is practically independent of the resistance. This is shown in figure 4. Therefore by differentiating equation 6 neglecting the resistance term and setting it to zero, the current corresponding to the critical stable voltage is expressible as:

$$I_m = -2\beta + \sqrt{\beta^2 + \frac{3\beta B}{(X_c - K_2)}} \tag{7}$$

Also, the current corresponding to the critical and release voltages for the case with a resistance less than the critical value can be expressed approximately by;

$$I_1 = -\beta + \sqrt{\frac{\beta B}{X_c - K_2 - R_0}} \tag{8}$$

$$I_2 = -\beta + \frac{B}{X_c - K_2 + 2R_0} \tag{9}$$

and the critical resistance found from equating the two equations above is;

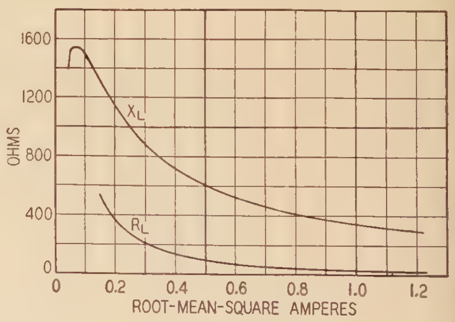
$$R_0 = -\frac{B}{8\beta} - \frac{1}{2}(X_c - K_2) + \sqrt{\left(\frac{B}{8\beta}\right)^2 + \frac{3B}{8\beta}(X_c - K_2)} \tag{10}$$

The critical stable voltage with a critical resistance in the circuit is then found by substituting R_0 and I_m in equation 5.

The equations derived in this analysis are found to be in very good agreement with the experimental values, the test being performed with four different reactors and various sizes of condensers. The tabulation of results with a comparison with the experimental values for one of the reactors is given in table I.

It is evident from these equations that the current jump increases as X_c decreases, as observed in figure 1, and when the value of the capacitance is equal to the constant K_2 of the reactor, the current rises to a very large value. Also, for this condition, the critical resistance will be equal to zero. For any resistance less than the critical value, the same analysis can be made, in which case the values of I_1 and I_2 must be used in calculating the critical and the release voltages. In summarizing the behavior of the series resonant circuit containing a nonlinear reactor, it can be stated that such a circuit is voltage sensitive in the critical region.

Figure 3. Reactance and apparent resistance (reactor 1)



The Parallel Circuit

Although the behavior of the parallel circuit was not studied in great detail, some points of interest will be briefly discussed. Figure 5 represents the volt-ampere relation of the parallel circuit, and instead of the circuit being voltage sensitive it is known to be current sensitive.

Table I (Reactor 1)

	Calculated Values			Experimental Values	
X_c	R_0	I_m	E	R_0	E
26	0				
43	18	2.48	322	30	323
93	55	1.13	282	60	284
188	113	0.653	245	114	248
272	151	0.490	218	145	224
355	178	0.395	200	170	205
460	206	0.305	186	190	186

As in the series circuit, the critical region characterized by the negative slope is some function of the resistance.

One thing of interest here is that the critical voltage and current for the reactor branch of the parallel circuit are essentially the same as those for the series circuit. Starting from the expression,

$$\frac{dI}{dE} = \frac{dI}{dI_L} \cdot \frac{dI_L}{dE} \tag{11}$$

the critical condition is found when $dI/dI_L = 0$, since dI_L/dE cannot become zero for any region. Neglecting the resistance,

$$I = -I_L \left\{ \frac{X_L - X_c}{X_c} \right\} \tag{12}$$

and when

$$\frac{dI}{dI_L} = 0$$

$$I_L \frac{dX_L}{dI_L} + X_L - X_c = 0 \tag{13}$$

When the expression for X_L is substituted into equation 13, the resulting equation becomes;

$$I_L = -\beta + \sqrt{\frac{\beta B}{X_c - K_2}} \tag{14}$$

and it is seen that this is essentially the same equation as that of the series circuit.

Since the reactor voltage is known for this current, and is also equal to the condenser voltage, the line current I is found by vector addition.

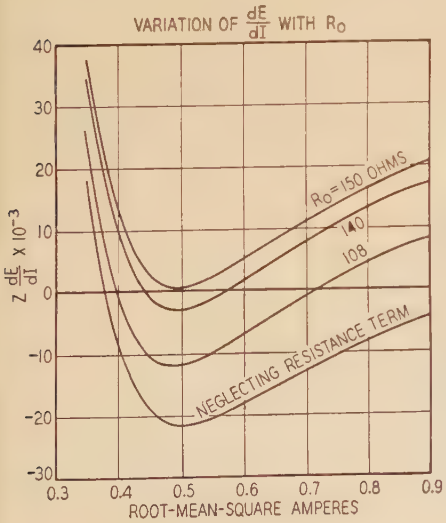
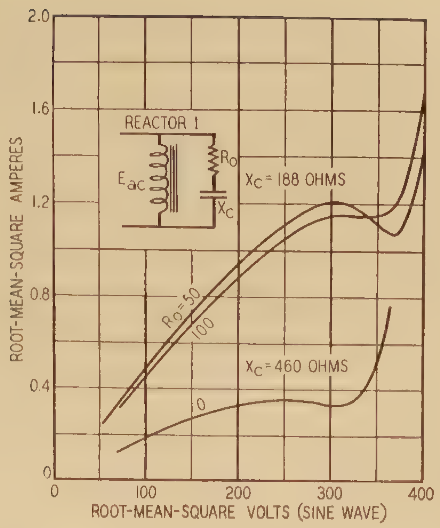


Figure 4

Figure 5. Characteristics of the parallel circuit



The Generalized Form of Reactance and Apparent Resistance

From the foregoing it is evident that in order to predict the behavior of the circuits discussed, the reactance and the apparent resistance of the reactor are necessary. The two quantities can be predicted approximately for any reactor provided certain experimental data for the iron are at hand.

The first of these is the effective permeability curve shown in figure 6. Since the reactance is

$$\frac{0.4\pi N^2 A}{l} \mu \times 10^{-8}$$

from this permeability curve, it is possible to determine the reactance of any reactor using the same iron.

In the same manner, the apparent resistance of any reactor can be obtained from the second curve of figure 6. This curve was calculated from the density-core-loss data and the a-c magnetization curve. The apparent resistance curve is obtained by multiplying the values of this last curve by $(N/l)^2$ and the number of pounds of iron used.

Although, in the method described above, the effect of the leakage flux and the air gap are assumed to be the same as that of the test reactor from which the data is obtained, the results obtained by this method agree very well with the actual curves.

The Series Circuit With D-C Saturation

Some points of interest in regards to the series resonant circuit with a d-c magnetizing force superimposed on the iron-core reactor was investigated mainly from the utility point of view.

To superimpose the d-c flux, the well-known three-legged reactor commonly used in controlling theater lighting was used. If the volt-ampere relation for such a reactor is plotted for various values of d-c saturation, it would be found that the effect of the d-c is to shift the magnetization curve to the right.[4] Also, the d-c saturation decreases the maximum of the reactance curve and

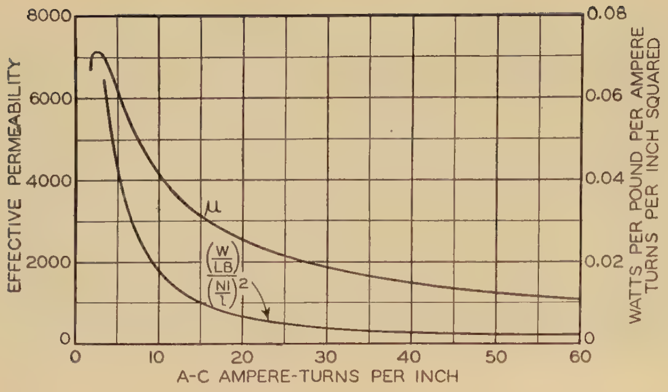


Figure 6. Generalized curves for reactance and apparent resistance

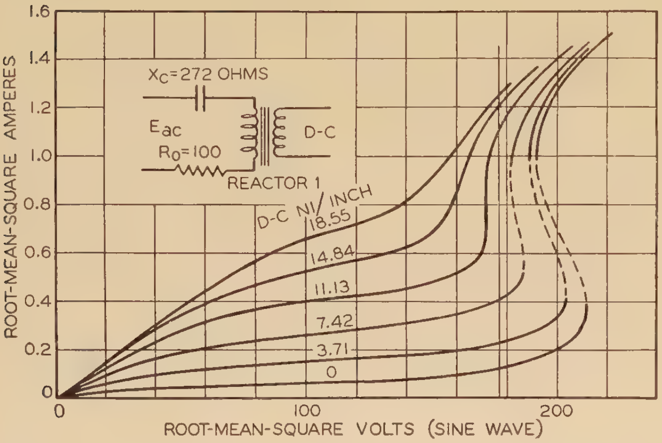


Figure 7. Series circuit with direct current superimposed

shifts it in the same direction. It will be found here that for a large value of a-c ampere-turns per inch, the reactance curves all come together and, therefore, in this region, the d-c controllability is greatly decreased. This will then determine for the d-c controlled circuit, the upper limit of the a-c ampere-turns per inch. The lower limit will obviously correspond to the peak of the reactance curve with zero d-c saturation. For the iron used in this investigation (Allegheny dynamo grade) the useful range of the a-c ampere-turns per inch is roughly between four and 30.

When the three-legged reactor is used in series with a condenser and a resistance, the volt-ampere relation will appear as in figure 7. Here it is noted that the effect of increasing the d-c saturation is to shift the curve upward and the critical voltage to the left.

When this circuit is operated with a constant voltage and the circuit controlled by the d-c coil, the locus of the a-c current will be along a vertical line such as that shown in the diagram, and it is seen that the change in the a-c current is greatest between certain values of d-c saturation as shown by curves 2 and 3. Therefore, if a very sensitive control is desired, it is possible to bring the circuit up to this sensitive level by means of another coil and operate the circuit about this region. By connecting two such circuits biased to this sensitive level in a bridge form, the initial output can be made equal to zero and the disturbing effect of the line-voltage fluctuation greatly eliminated.

When operating with a d-c bias, some difficulty is encountered when the controlling power is very small. This is due to the fact that with a d-c level of magnetization, there is a voltage induced in the control coil which may render the circuit unstable. With a d-c level of saturation, the flux variation in the two a-c legs of the reactor becomes unequal. The difference in these two fluxes must then flow through the center leg of the reactor, thereby inducing a voltage in the control coil. An analysis from the magnetization curve indicates that this unbalance of flux is mainly in the opposite direction to that of the control coil, and therefore is demagnetizing. For these reasons, it is advantageous to prevent this unbalance of flux from flowing in the center leg. This is accomplished by placing a short-circuited coil around the d-c leg.

With this short-circuited coil, an interesting difficulty was encountered. If the resistance R_0 in the circuit is reduced to a value less than the critical resistance, the circuit goes into a low-frequency oscillation. The oscillogram of figure 8 illustrates this phenomenon. It is found that the frequency of this oscillation is mainly a function of the d-c magnetizing force. This low-frequency oscillation, however, was checked by increasing the resistance to a value greater than the critical resistance of the circuit.

A Regenerative Method of Increasing the Sensitivity of the D-C Controlled Circuit

Noting that in any amplifying device if a part of the output is fed back to the input, the over-all gain is greatly increased, a scheme similar to that of the regenerative

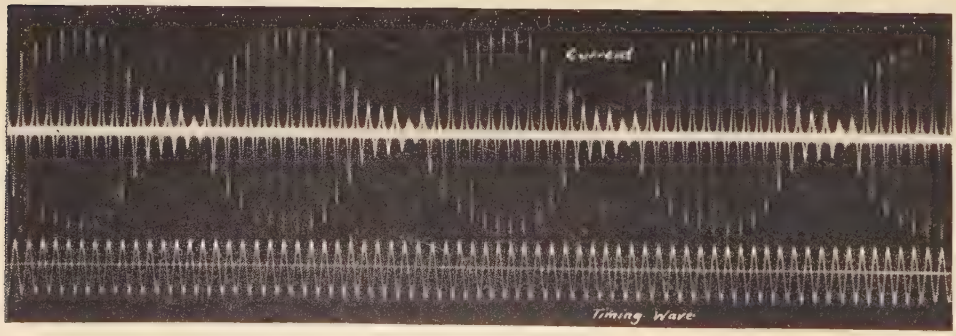


Figure 8. Low-frequency oscillation

radio circuit can be used to increase the sensitivity of the d-c controlled circuit.

Figure 9 indicates the circuit diagram of the regenerative amplifier. The a-c output obtained across the condenser is rectified by means of the copper-oxide rectifier to supply the d-c load, the circuit being controlled by the d-c saturation. The amplification is obtained by feeding the output current through a regeneration coil wound on the same leg as the d-c control coil, the effect being to increase the total control of the circuit. With such a scheme, if the number of turns on the regeneration coil is too large, the circuit becomes unstable and therefore some criteria for the stability as well as the amplification must be developed. This is done by first assuming a straight-line relation between the input and the output current and developing the mathematics by a step-by-step process.

Starting with an input of i_0, the initial output current will be hi_0, where h is the slope of the output current for zero regeneration. This output flowing through the regeneration coil produces an additional control of $(nh/N)i_0$, which must be added to the initial control to give the effective control. Continuing with this process, the resulting equation is a geometric series,

$$I_{output} = hi_0 \left\{1 + \left(\frac{nh}{N}\right) + \left(\frac{nh}{N}\right)^2 + \left(\frac{nh}{N}\right)^3 + \ldots\right\} \tag{15}$$

the sum of which is given by the following equation:

$$I_{output} = hi_0 \left\{\frac{1}{1 - \left(\frac{nh}{N}\right)}\right\} \tag{16}$$

where

n = number of turns on the regeneration coil
N = number of turns on the control coil
h = slope of the initial curve with no regeneration
i_0 = control current
I_{output} = output current with regeneration

From this equation it is evident that the circuit is stable as long as (nh/N) remains less than one, and therefore this becomes the criterion for stability. The amplification factor is given by the bracketed term. For the case where the initial response curve deviates greatly from the linear relation, better results can be obtained by using the following equation,

$$I_{output} = I' \left\{\frac{1}{1 - \left(\frac{nh'}{N}\right)}\right\} \tag{17}$$

where

I' = actual current for no regeneration, at the point in consideration
h' = actual slope of the curve corresponding to the point in question

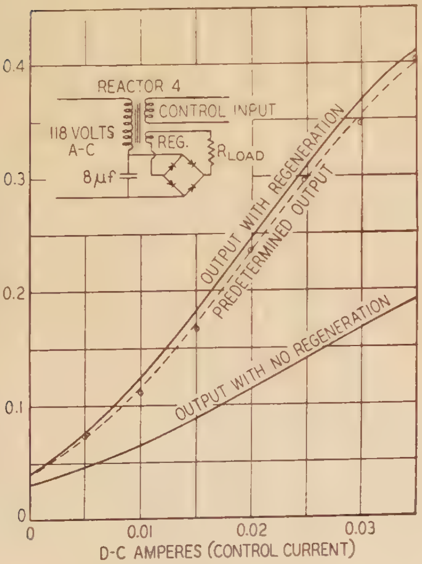


Figure 9. Regenerative amplifier

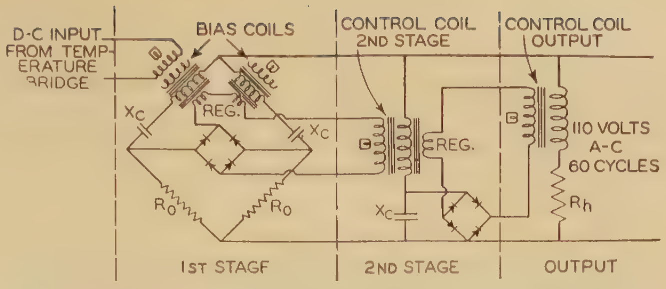


Figure 10. Control circuit of radiation meter

To verify this equation, several predeterminations were made, one of which is shown in figure 9. In this diagram, the lower curve is the output plotted in terms of the input for no regeneration, while the upper solid curve represents the output of the same circuit with regeneration. The dotted curve is the predetermined output calculated from equation 17, and it is seen that the agreement between the theoretical and the experimental curves is very close.

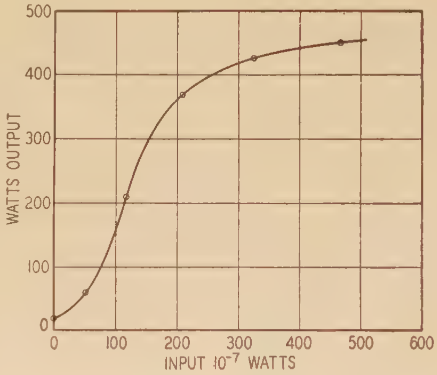


Figure 11. Output curve of the radiation meter

A Specific Application to the Radiation-Meter Control Circuit

The circuits discussed in this paper have been successfully applied to a specific engineering problem in connection with the radiation meter. The function of this meter is to measure the net radiation taking place at the earth's surface, such data having important applications in the study of plants.

These measurements must be taken continuously for a long period extending into years. It is necessary to maintain control without the use of contactors, relays, or other intermittent devices and also without the use of units, such as vacuum tubes, which would require frequent replacements.

Briefly, the radiation meter consists of two exposure plates, one black and the other bright, which are kept at the same constant temperature. Since the convection and conduction losses under this condition are equal, the differential heat input necessary to maintain this constant temperature is a measure of the net radiation. This differential power is recorded continuously by a graphic differential wattmeter.

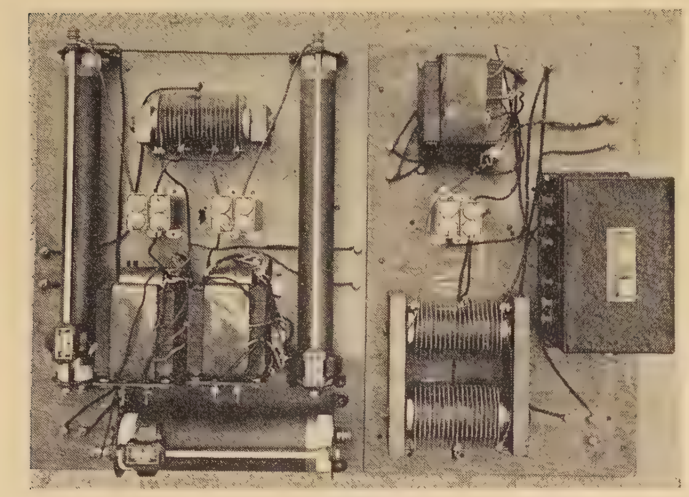


Figure 12

Figure 10 shows the control for one of the exposure plates and represents half of the radiation meter. In this R_h represents the heating loads for one of the constant-temperature surfaces, connected in series with a saturable-core reactor. The power for the control input is obtained from a temperature-bridge thermometer imbedded in the same constant-temperature surface. For a two-degree deviation from the set temperature, the temperature bridge sends a signal into the control circuit sufficient to produce maximum heating at the heater coil.

The first stage of this control circuit is connected in a bridge to overcome any effect of line voltage fluctuation, and each arm of the bridge is biased to the most sensitive level by means of the bias coils. The output of this bridge is then rectified by means of the copper-oxide rectifier and fed through the regeneration coils and the control coil of the second stage. The connection of the regeneration coils in the bridge is such that it aids the bias and the control signal in the first leg and opposes the bias in the second leg, thereby producing a maximum of unbalance. In the same manner, the output of the second stage is rectified and fed through the regeneration coil and the control coil of the final stage. Here the bridge circuit is not necessary since the control signal is sufficiently large and the effect of the line voltage fluctuation relatively small.

The amplification obtainable from such a circuit is quite striking as shown by the curve giving the over-all characteristics of the control circuit. (See figure 11.) It is seen here that an input of 450×10^{-7} watts is sufficient to control an output of approximately 450 watts, thereby resulting in a power amplification of approximately 10,000,000. Such a circuit is quite inexpensive to build, and once the control is adjusted, the circuit will require practically no replacement of parts or upkeep for service. The simplicity of this control circuit is shown by the photograph of figure 12.

In conclusion it may be stated that the greatest utility of such circuits will undoubtedly be in control circuits where large amounts of power must be continuously controlled by means of a relatively small input. As more and more becomes known of such circuits, the resonant type of nonlinear circuit will find a definite place in the various engineering fields.

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Discussion

P. H. Odessey (Heyer Products Company, Belleville, N. J.): In Mr. Thomson's paper, the derivation of critical quantities associated with ferroresonance embodies a number of concepts that are not quite clear. In particular, the following points are noted with respect to approximations and assumptions made in deriving the expressions for current and critical resistance as defined in this paper; the numbers of equations are those used in the paper.

1. The current (7) corresponding to the "critical stable" voltage is derived from the relation

$$\frac{d^2E}{dI^2} = 0$$

whereby the resistance is neglected. The assumption that this current is practically independent of resistance is an approximation that is valid for a particular type of reactor, that is, if the a-c volt-ampere characteristic is relatively steep and bends sharply at high saturation. For the type of characteristic whose slope changes slowly with saturation considerable error is introduced by neglecting resistance. The experimental results of Rouelle (*R.G.E.* 1934) give evidence of this effect. The resulting equation for current (7) contains a radical and hence should reveal two distinct values of current. No explanation is given for discarding one of these values nor of the significance of the negative sign before the radical.

2. When current is defined by (7), the corresponding value of critical stable voltage evaluated by means of (5) must be determined by using the value of critical resistance R_0 defined by (10). As there is no interrelation between I_m and R_0 the justification for this step

is not quite clear. Thus, employing the criteria of stability,

$$\frac{dE}{dI} = 0$$

two "approximate" equations are given for the currents corresponding to the release voltages and contain a resistance term R_0. Since equation (6) was stated to be mathematically unsolvable when resistance was included, it is not quite clear how (8) and (9) were derived. As the forms of these equations indicate, their derivation does not follow as an approximation made after solving (6) by neglecting resistance.

3. Since these two equations are identical for the condition of critical stable voltage, the analytic expression for critical resistance (10) is obtained by equating (8) and (9). But since (7) already expresses the value of current corresponding to the critical stable voltage, then (8) and (9) could each be made identical with (7) and two other equations for critical resistance could be obtained. This discrepancy is not explained.

4. If, as in the presentation, the critical resistance is properly expressed, then by substituting this value (10) in the current equations (8) or (9) we should obtain equivalence with I_m defined by (7). There is, however, no assurance that this may be attained even approximately. It appears, therefore, that the critical resistance and I_m are entirely unrelated, yet must be employed together in the evaluation of critical stable voltage by means of (5).

5. In view of the assumptions and approximations, the results indicate an unusually high degree of accuracy although not consistent. For example, corresponding to a 40 per cent error in R_0 (X_c = 43, table I) the error in critical stable voltage is 0.3 per cent whereas for a 0.88 per cent error in R_0, the error in voltage is 1.21 per cent (X_c = 188). Thus, it appears that any error in R_0 does not materially affect the value of voltage. Although not given, it would have been interesting to observe the check on I_m, I_1 and I_2, and so justify some of the approximations.

W. T. Thomson: In reply to Mr. Odessey's discussion, I will endeavor to justify the assumptions made and indicate why it is possible to arrive at accurate results for the critical voltage using the more inaccurate values of critical current and resistance. Dimensions of one of the reactors for which the results were published are given together with the sample calculations (see figure 2).

Although my investigation was limited to a certain type of reactor (three-legged reactor) using a certain grade of iron, this type of reactor is extensively used for various control purposes and quite frequently with iron of similar characteristics. It seems therefore that Mr. Odessey's criticism that the method is applicable only to a very special and limited condition is not justifiable.

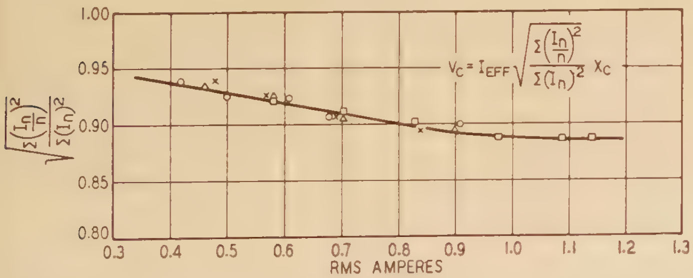
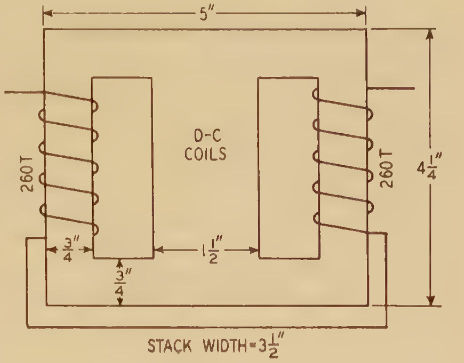


Figure 1. Reduction in voltage across condenser due to harmonics

$$V_c = I_{eff}\sqrt{\frac{\Sigma\left(\frac{I_n}{n}\right)^2}{\Sigma(I_n)^2}}\,X_c$$

The apparent resistance of the reactor defined by the expression $R_L = W/I^2$ is of course an approximation for circuits containing iron. It is agreed that for small values of current this error is not great. Let us investigate then the discrepancy for a large value of current. Assume in figure 3 that $I_1 = 0.8I$ when $I = 1.2$ amperes. R_L from the curve is 15 ohms and its value based on I_1 is $15/0.8^2 = 23.5$ ohms. The per cent error is therefore considerable but the difference in ohms is only 8.5. In the calculation of the voltage this small error in a term which is small compared to the reactive term produces practically no error when combined at right angles.

Figure 2. Dimensions of reactor 1



It may be stated that in order to obtain values for the more correct definition based on the fundamental current I_1, special equipment such as the harmonic analyzer is necessary, and for the average person to whom such equipment is not available, an approximation of this type is not out of order as long as it produces negligible errors in the final results. The writer would like to point out that Mr. Odessey in his paper ("Critical Conditions in Ferroresonance") makes an approximation which is far more serious in assuming the first term of equation 4 to be an ellipse. This term of the equation is an ellipse only when the total resistance is constant. The apparent resistance which must be considered as part of the total resistance varies greatly with the current as shown in figure 3.

Equations 8 and 9 are empirical. When $R_0 = 0$, they are the roots of equation 6 with the resistance omitted. The expression for R_0 given by equation 10 is therefore empirical and is unrelated to I_m as stated in the paper. To show that equation 10 is not a special equation limited only to a certain reactor, the following results obtained for three other three-legged reactors made with the same iron are given.

Reactor 3			Reactor 2			Reactor 4		
X_c	R_0 (Calc.)	R_0 (Exp.)	X_c	R_0 (Calc.)	R_0 (Exp.)	X_c	R_0 (Calc.)	R_0 (Exp.)
93	57	63	25	8	10	93	47	56
187	120	120	43	24	26	187	108	107
272	162	164	93	49	50	272	146	139
355	194	182	187	75	68	339	172	158
			272	87	75			

As stated before, a few ohms error one way or another when combined at quadrature with a much larger reactive term produces negligible error in the calculation of the voltage.

Equation 7 will always give a value of current in the unstable region. It is apparent from figure 1 that with a critical stable condition the current may have a wide range of values and still give the same critical voltage. Therefore even if this current varied with resistance for other types of iron, very little error would be produced in the critical voltage provided the current obtained is within the unstable region.

I fail to see any physical significance of the negative sign in front of the radical in equation 7. The equations as given in my paper apply only in as far as they fit the experimental curves for X_L

and for this case the negative value of the effective current seems meaningless.

Appendix

I. SAMPLE CALCULATION

For Reactor 1:

$$X_L = \frac{360}{0.115 + I} + 26$$

Therefore $B = 360$

$\beta = 0.115$
$K_2 = 26$

For $X_c = 272$ *ohms:*

$$R_0 = -\frac{360}{8 \times 0.115} - \frac{1}{2}(272 - 26) + \sqrt{\left(\frac{360}{8 \times 0.115}\right)^2 + \left(\frac{3 \times 360}{8 \times 0.115}\right)(272 - 26)} = 151 \text{ ohms}$$

$$I_m = -2 \times 0.115 + \sqrt{(0.115)^2 + \frac{3 \times 0.115 \times 360}{272 - 26}} = 0.49 \text{ ampere}$$

therefore

$X_L = 620$
$R_L = 100$

From figure 1

$$\sqrt{\frac{\Sigma\left(\frac{I_n}{n}\right)^2}{\Sigma I_n{}^2}} = 0.93$$

$$E = 0.49\sqrt{(100 + 151)^2 + (620 - 0.93 \times 272)^2} = 218 \text{ volts}$$

II. DATA FOR REGENERATION CURVE, FIGURE 9

Reactor 4:

Control and regeneration coils on center leg

$n = 200$
$N = 2{,}000$

therefore

$$I_{dc} = I^1 \left\{\frac{1}{1 - 0.1K}\right\}$$

Discussions

of AIEE Technical Papers Published Before Discussions Were Available

ON THIS and the following 15 pages appear discussions submitted for publication, and approved by the technical committees, on previously published papers presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Matrices in Engineering

Discussion and author's closure of a paper by Louis A. Pipes published on pages 1177–90 of volume 56, 1937, AIEE TRANSACTIONS (September 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the basic sciences session of the winter convention, New York, N. Y., January 26, 1938.

Joseph Slepian (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Linear systems of equations such as are continually met in practical engineering problems, present their primary data to us in the form of a rectangular array of numbers, the coefficients of the various terms in the set of equations. All the information which it is possible to obtain mathematically about the physical system represented by the equations is buried or latent in this array of numbers. Whatever new information we succeed in arriving at about the system by purely mathematical means will be reached ultimately only by successions of arithmetical operations upon the numbers of the array. Hence, we may say that this rectangular array of numbers is the appropriate manner of mathematical description or representation of the physical system for which the linear system of equations was set down. Given the sufficient description of the kind of equations for which the numbers serve as coefficients, the array gives all the information about the system with no irrelevancy. Both the position in the array of a number and its magnitude are significant in determining the result of any actual calculation.

Thus the matrix as an entity presents itself naturally and easily from the study of systems of linear equations. The various manipulations we make upon linear equations amount always to the calculation of new (usually simpler) matrices from given matrices. Thus the idea of a matrix calculus arises.

Two particular ways of calculating a new matrix from two other matrices keep recurring in practical problems. Because of their similarity to the arithmetic operations of addition and multiplication of ordinary numbers, they are called matrix addition and matrix multiplication. Thus we have a matrix algebra which is similar, except for one important property, to ordinary algebra. The beauty and utility of this matrix algebra applied to important every day problems in electrical engineering are well brought out in the very excellent paper by Professor Reed.

A finite number of applications of the operations of addition and multiplication of matrices will, of course, yield only polynomials, but Pipes in his remarkable paper shows the practical value of considering an infinite number of applications of these operations, as in a power series, thus arriving at the notion of more general functions of matrices. Then the beautiful, powerful, but little-known Cayley-Hamilton Theorem shows that these general functions of a matrix are not nearly as complicated as one might first expect, but reduce to simple sums of these functions of the latent roots of the matrix with easily expressed matrix coefficients.

I believe that this is the first time that the Cayley-Hamilton Theorem has appeared in ELECTRICAL ENGINEERING. Pipes is to be highly commended for calling this powerful tool to the attention of electrical engineers, particularly as he gets down to brass tacks in his remarkable paper, and for several well chosen examples, shows how by proper use of this theorem, numerical results are quickly and easily reached. I hope this paper will receive the wide and careful attention it deserves, and that it will stimulate the further proper application of higher mathematics to electrical engineering problems.

Louis A. Pipes: Doctor Slepian summarizes the utility and power of matrix algebra in the usual engineering problem leading to a discussion of linear dynamical system in a most concise and comprehensive manner.

There appears to be some confusion among some engineers concerning the relation of matrix algebra to tensor algebra. It should be realized that a matrix may be regarded as a tensor of the second rank with respect to a linear transformation. Since practically all the equations met in practical engineering problems are linear, linear transformations are encountered and consequently the summation convention, upper and lower indices, and other tensor machinery may be dispensed with and the classical matrix notation employed.

Matrix theory has received a great deal of attention by the mathematicians and many powerful theorems exist in the mathematical literature which have great practical importance. By the use of these theorems, the solution of polynomial equations, the calculation of normal modes, and other processes of great importance in engineering and physics may be most easily accomplished.

In conclusion, it should be pointed out that on page 1178 of the paper "Matrices in Engineering" the last word in section *D* should be "commutative" and not "symmetric."

The Properties of Three-Phase Systems Deduced With the Aid of Matrices

Discussion and author's closure of a paper by M. B. Reed published on pages 74–7 of this volume (February section), and presented for oral discussion at the basic sciences session of the winter convention, New York, N. Y., January 26, 1938.

Joseph Slepian: For discussion, see this page.

Irven Travis (University of Pennsylvania, Philadelphia): I agree most heartily with Mr. Reed that the matrix formulation of electric circuit problems clears away the algebraic debris and thus more clearly reveals the main line of reasoning. Mr. Reed has given a number of very interesting examples.

There is one point which I should like to amplify. Below equation 39 is the statement, "This equation cannot be used to determine E_{pg} in terms of I_{pg} because of the singularity of the transformation. Further investigation will show that no relation can be found for E_{pg} in terms of I_{pg}, and the circuit impedances or admittances; i.e., given a set of wye-connected impedances and the line currents, the phase generator voltages of the source cannot be computed." Although it is true that there are infinitely many voltages which will satisfy the system, valuable information can be obtained by transforming equation 39 to symmetrical co-ordinates.

Let the matrix S be defined as

$$S = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \tag{1}$$

where

$$a = \epsilon^{j\frac{2\pi}{3}}$$

Multiplying both sides of equation 39 by S and inserting $S \cdot S^{-1} =$

U_1 in the product on the right hand side, we have

$$(SI_{pg}) = (ST_yYT_{Yt}S^{-1})(SE_{pg}) \tag{2}$$

By expanding (SI_{pg}) and (SE_{pg}) it is easy to see that

$$SI_{pg} = (I_{A10}, I_{A11}, I_{A12}) \tag{3}$$

$$SE_{pg} = (E_{100}, E_{101}, E_{102}) \tag{4}$$

in which the added subscript (0, 1, 2) denotes a zero-, positive- or negative-sequence quantity.

Let Y, which is the inverse of 32, be denoted by

$$Y = \begin{pmatrix} y_{11} & y_{12} \\ y_{12} & y_{22} \end{pmatrix} \tag{5}$$

then the product on the right hand side of equation 2 is

$$ST_yYT_{Yt}S^{-1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{11} - y_{12} + y_{22} & -(ay_{11} + 2a^2y_{12} + y_{22} \\ 0 & -(a^2y_{11} + 2ay_{12} + y_{22}) & y_{11} - y_{12} + y_{22} \end{pmatrix}$$

Equation 2 is therefore of the form

$$I'_{pg} = Y'E'_{pg} \tag{6}$$

where

$$I'_{pg} = (I_{A11}, I_{A12}) \tag{7}$$

$$E'_{pg} = (E_{101}, E_{102}) \tag{8}$$

$$Y' = \begin{pmatrix} (y_{11} - y_{12} + y_{22}) & -(ay_{11} + 2a^2y_{12} + y_{22}) \\ -(a^2y_{11} + 2ay_{12} + y_{22}) & (y_{11} - y_{12} + y_{22}) \end{pmatrix} \tag{9}$$

The matrix Y' is not singular, hence it is possible to express the positive- and negative-sequence components of the generator phase voltages in terms of the phase currents and the circuit impedances. Thus the phase voltages are arbitrary because their zero-sequence components are arbitrary, but they cannot be assigned any values at random as might be inferred from the statement below equation 39.

M. B. Reed: As Mr. Travis points out, the generator phase voltages of a wye system are arbitrary only through the arbitrariness of the zero-sequence component of these voltages. This voltage component may have any one of a doubly-infinite set of values—any one of an infinite set of lengths, for a particular position or any one of an infinite set of positions for a particular length—and still the phase voltages will give the same set of line voltages. This result can be readily shown without recourse to symmetrical components as follows:

If the point at the center of gravity *cg* of the line-voltage triangle is designed by o'

$$\mathfrak{E}_{Lg} = \mathfrak{U}_{12}\mathfrak{E}'_{pg} = \mathfrak{U}_{12}(E_{10'}, E_{20'}, E_{30'}). \tag{1}$$

Since $\mathfrak{U}_{12}$ is singular, this transformation is irreversible. However, if the relation

$$E_{10'} + E_{20'} + E_{80'} = 0$$

is used to eliminate $E_{80'}$ from the first two of the equations represented by (1), and if the third equation is omitted, the result is

$$\mathfrak{E} = \begin{pmatrix} 1 & -1 \\ 1 & 2 \end{pmatrix} (E_{10'}, E_{20'}) = \begin{pmatrix} 1 & -1 \\ 1 & 2 \end{pmatrix} \mathfrak{E}' \tag{2}$$

and since the transformation matrix is nonsingular

$$\mathfrak{E}' = \frac{1}{3} \begin{pmatrix} 2 & 1 \\ -1 & 1 \end{pmatrix} \mathfrak{E} \tag{3}$$

i.e., the voltages to the *cg* of the line-voltage triangle determine the line voltages. But from the fact that

$$\mathfrak{I} = \mathfrak{Y}\mathfrak{E} = \mathfrak{Y} \begin{pmatrix} 1 & -1 \\ 1 & 2 \end{pmatrix} \mathfrak{E}' \tag{4}$$

evidently the currents are completely determined from the voltages to the *cg* of the line-voltage triangle. Further since

$$\mathfrak{E}_{pg} = \mathfrak{E}'_{pg} + E_{o'o}(1,1,1) \tag{5}$$

it is evident that $E_{o'o}$, the voltage between the common point o of the generator and the *cg* of the line-voltage triangle, is the arbitrary element in the phase voltages of the generator, and further that $E_{o'o}$ has no effect on the currents in the system no matter what its value.

Corona Voltages of Typical Transformer Insulations Under Oil

Discussion and author's closure of a paper by F. J. Vogel published on pages 34–6 of this volume (January section), and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 27, 1938.

I. W. Gross: For discussion, see page 194 of this volume (April section).

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): Mr. Vogel's paper is of considerable interest to me as it deals with a subject along my line of work.

I wish to discuss it from several viewpoints.

Mr. Vogel's experience with the harmful effects of air in his barrier parallels closely my own experience. As stated in my paper I found that any air at all in the structure gave misleading results and I found it necessary to assemble the sample under oil, not allowing the small coil used as the line electrode to come in contact with air after vacuum treatment and oil impregnation.

I subscribe 100 per cent to his second conclusion in that it is very important to remove all entrapped air in transformers before making commercial tests at the factory. Also if high-voltage transformers are not shipped filled with oil or are untanked for inspection, special means should be taken to remove the air. If a vacuum cannot be applied, one of the best means of getting the air out is to make a short-circuit heat run. Laboratory tests have shown that if oil is circulated by an air pocket it takes only a few hours to absorb the air. Tipping the transformer often is helpful in removing air pockets that are not adjacent to the oil in circulation.

I note that Mr. Vogel obtained an impulse ratio in the order of 2 to 2.3. My own tests do not bear this out. I have found that the ratio varies over a much wider range, depending on the construction of the sample. Based on the tests given in my paper and on the injurious corona voltage, I found a ratio of 1.75 for barrier *C* and 2.48 for barrier *D*. Barrier *C* had a spacing of 0.641 inch from the coil to ground and *D* a spacing of 2.5 inches from the coil to ground. I cannot agree, therefore, that there is a constant impulse ratio for all voltage ratings of transformers.

Mr. Vogel's statement that the dielectric strength varies approximately as the barrier thickness raised to the two-thirds power checks my experience. I have used this two-thirds-power rule for several years. I have found that the dielectric strength of oil when tested with edged electrodes or with round rods varies with the spacing raised to the two-thirds power. However, if tested in a uniform dielectric field it varies more nearly in proportion to the spacing. I believe that cable engineers have found that the strength of the paper covering varies approximately as the thickness. While cable insulation is stressed highest next to the bare part of the cable on account of its reduced periphery, the conditions are such that it corresponds fairly well with a uniform field. That is, there are no sharp corners or edges to cause voltage concentrations.

I believe it can be said, therefore, that the two-thirds-power law is not inherent in the characteristics of the material—solid or oil—but by the shape of the electrodes.

Conditions in transformers are such that most all insulations are in nonuniform fields and on this account we must generally increase the insulations faster than the test kilovolts. Roughly speaking, by the two-thirds rule, if the test is doubled, the distance or insulation must be trebled. This explains why the cost and size of transformers increases so fast with voltage.

L. H. Hill (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): It is interesting to note from Mr. Vogel's paper that as a result of his impulse tests he has reached the conclusion that transformers should be filled with oil under a vacuum.

The company with which I am associated has been filling high-voltage transformers with oil under a vacuum for about five years, and repeated tests have indicated the desirability of going to that extra trouble. In connection with filling transformers under vacuum, we have found that the method of filling the transformer tanks with oil has considerable bearing on the amount of time required to do this. If the transformer tank is filled from the bottom, we have found that it may take as long as four days for the surplus air to come out of the oil; however, if the transformer tank is filled by running the oil in at the top so that the oil goes into the transformer as a foam, by the time the transformer tank has been filled, the oil is perfectly quiet, indicating that all the air has been removed.

From a practical point of view, the increased cost of building transformer tanks so that oil could be installed in the field with the tanks under a vacuum would not be very great.

Eric A. Walker (Tufts College, Mass.): Mr. Vogel, in his paper, has undoubtedly opened a field which may well help us to discover more of the factors which lead to the breakdown of fibrous insulation under oil.

In this paper Mr. Vogel mentions the detection of corona by audible frequencies only, that is, directly by ear or by the use of a microphone.

There are at least three methods by which corona may be detected. An audible method as described by Mr. Vogel makes use of the energy in a limited frequency range. A radio-frequency detector and amplifier, used in the radio- and intermediate-frequency ranges, has met with some success. One can also find the corona voltage by power-factor measurements and ascertaining the point at which there is an abrupt rise in power factor. In a recent investigation, in which the three methods were compared, the power-factor method showed a lower critical voltage than the other two methods. In another investigation, on a system of concentric electrodes separated by several layers of fibrous insulation, it was possible to detect when each layer of occluded air became ionized by a sudden increase in power factor. Of course such a method would not give a definite point on a large transformer unless the corona became quite general.

The second consideration in this paper is its effect on operating practices. It is recognized that the first few days during which a transformer is energized are critical ones. This is probably more true of transformers which have served some time as spare transformers than of new ones. Failures during this critical period have usually been attributed to the absorption of moisture by the fibrous insulation. Although evidence indicates that the insulation does absorb moisture by breathing there is no proof that moisture alone is the only cause or even the principal cause of deterioration. Now Mr. Vogel points out that occluded gases may lower the corona voltage. This will cause "tracking" which would not take place if the gas were not present as is usually true in normal operation. This type of deterioration may well be more serious than the absorption of moisture for the damage caused by such carbonization is permanent and cannot be remedied as the absorption of moisture can be by a mere drying process.

Ultimately it will be desirable to detect the formation of corona in transformers in service, both during normal operation and during overvoltage tests. It is extremely doubtful if aural methods would be sufficient for such tests. Radio-frequency tests are difficult to use because of the normal corona in substations. A power factor test would have a wide application as a field test where the moisture content of the insulation is important as well as the voltage at which corona is initiated. Such a test also has the advantage of being a nondestructive test if applied at, or below, the operating voltage.

J. O. Fenwick (Line Material Company, South Milwaukee, Wis.): Mr. Vogel's paper on "Corona and Oil-Impregnated Insulation" describes one of several lines of investigations now being pursued in the improvement of transformer insulation, particularly against lightning surges. Elaborate studies, such as outlined in this paper, are ordinarily considered as being confined to large power transformers, but similar investigations are now being adopted in the development of distribution transformers as well. Such studies are of particular value in the design of rural-type transformers where exposure to lightning is severe and protection is not of the best. Other parallel lines of investigation on insulation are studies of power factor of the insulation, radio interference, as well as the more familiar puncture tests on 60-cycle and impulse voltages.

The corona test described by Mr. Vogel as well as the radio-noise and power-factor studies give valuable information not shown by the more conventional puncture tests. For one thing, this specimen under test need not be totally destroyed as is frequently the case with puncture tests and yet the voltage can be raised to the point at which the insulation begins to show signs of distress as manifested by the corona markings mentioned by Mr. Vogel, or by radio noise where this is used as an indication of corona. Very often a better picture of the electrostatic field is obtained and corrected measures can be applied more intelligently than is the case where the test specimen is totally destroyed.

Another result is that since corona is one of the first immediate indications of over-stressed insulation, the corona voltage is somewhat analogous to the "yield point" of a metal specimen with mechanical loading and the value of this information to the designer is obvious.

The point not emphasized by Mr. Vogel is the uncertainty of results and limited conclusions that can be drawn unless a great amount of test data is accumulated. The voltage resulting in corona and ultimate puncture of the specimen depends so much upon the shape of the electrodes, presence of sharp corners, and other such incidental factors that a seemingly comprehensive test often gives results which are rendered nearly valueless when some apparently minor change is made in the method of test. For this reason, tests made with electrodes and specimens which appear to simulate conditions in the actual transformer often give misleading results as far as numerical design data is concerned, and a large amount of testing must be done in order to obtain even a moderate amount of reliable and usable information.

The seeming inconsistency of the results of insulation studies is illustrated by a comparison of the results reported by Mr. Vogel and others obtained by our own company. Mr. Vogel reports a ratio of roughly two to one between impulse puncture and 60-cycle corona voltage. Our own tests on samples of insulation and also assembled transformers indicate that this ratio, instead of being two to one as reported by Mr. Vogel, for well-impregnated specimens, may vary as much as ten to one, for certain peculiar conditions of test. Our results do emphasize, however, the importance of thorough impregnation and the necessity for eliminating air from the test specimen if consistent results are to be obtained. The results are of considerable value in giving the designer a "feel" of the distribution of the electrostatic field, but as indicated in the foregoing, the numerical results must be used with considerable caution.

F. J. Vogel: I was greatly interested in Mr. Montsinger's discussion, inasmuch as he found that the air entrapped in insulation structures caused them to give erratic results, and in his agreement with me that it was important to remove all entrapped air in transformers before making commercial tests at the factory. It is my opinion, based on our tests, that higher values can be obtained by vacuum filling than by removing air in any other way. Our own experience has been that transformers in service as long as a year and a half may still have entrapped air which can result in a failure. Therefore, vacuum filling would seem to be essential even in the field if maximum dielectric strength and certainty were to be obtained.

I agree with Mr. Montsinger that it is possible to obtain impulse ratios over quite a range. However, I have tried to be careful to limit the application of the 2.2 ratio to a specific type of construction. My paper covered only barriers with interleaved insulation. Depending upon the interpretation of Mr. Montsinger's data for barrier *D*, somewhat lower values than 2.48 might be given. I have tried to be conservative in this to furnish values which could be expected rather than the maximum values. Barrier *C* is not of the same construction and, as stated in my discussion of his paper, I do not believe that his construction is typical of any insulation structure actually used in a transformer.

With relation to the dielectric strength of oil in uniform fields, or in fields due to edged electrodes or round rods, it is interesting to note Mr. Montsinger's findings, and I believe this is a subject which is worthy of a future paper.

The future of power-factor tests on transformers is uncertain in the writer's opinion. Data which we have to date indicate that corona even in service is unlikely. To detect corona by power-factor measurements with present-day equipment seems impossible.

The question of using voltage measurements and times only, instead of gap lengths for specifications and test purposes, seems to be evading the issue. One organization of consulting engineers specifies gaps to be installed at the terminals of their transformers. They specify that a voltage wave of given steepness be impressed upon the transformer to prove the transformer will withstand this condition. The purpose of this test undoubtedly is to prove that the transformer with the gap installed in service will be protected against failure of the transformer windings. If voltage data from one source is used to specify the voltage to be applied, and the tests on the unit are not made in the laboratory where these readings agree, it might be possible to obtain a transformer which would not withstand the operating conditions desired by the purchaser. It seems to the writer that it is better to use a direct method of test rather than to use an intermediate step where there is a possibility of error.

I believe that the previous discussions show clearly that it is possible to increase the impulse strength of commercially oil-insulated transformers by admitting the oil to the tank while the winding is still under vacuum. It should be possible to do this in the field and, with special equipment filtering the oil, should be possible without even a temporary reduction in impulse strength from transferring the oil. The per cent increase in strength, due to vacuum-filling, as compared to nonvacuum filling, is variable.

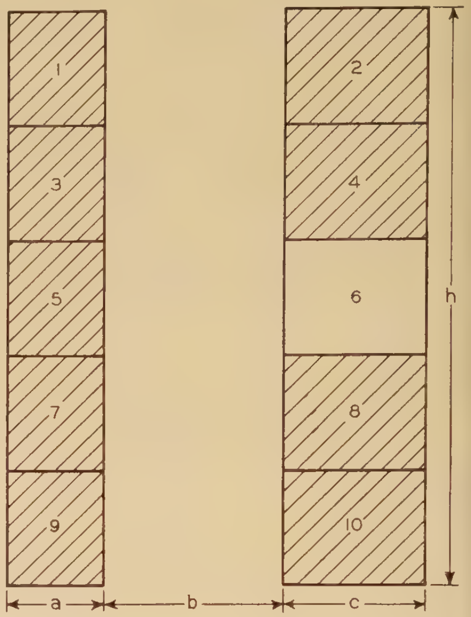
A Formula for the Reactance of the Interleaved Component of Transformers

Discussion and authors' closures of a paper by H. B. Dwight and L. S. Dzung published on pages 1368–71 of volume 56, 1937, AIEE TRANSACTIONS (November 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 27, 1938.

A. N. Garin (General Electric Company, Pittsfield, Mass.): A theoretically rigorous solution of the problem of transformer reactance presents many difficulties due to the complexity of the physical structure of transformers. The factors chiefly responsible for these difficulties are: the curvature of windings, the presence of core iron, and the nonuniformity in the turn distribution in the cross section of windings. A practical engineering solution consists, therefore, first, of idealizing the structure until it is amenable to calculation by one of the theoretical methods available; second, of selecting the theoretical method best suited for the purpose and of performing the calculation; and third, of applying to the result of the theoretical calculation, whenever necessary, an empirical correction factor, which should not exceed a few per cent of the calculated value. Thus, calculation of reactance for a modern complicated transformer is not science, but an art, based on science.

The present trend in transformer design naturally results in a race between the growing complexity of windings and the increasing skill of the reactance calculator. The reactance calculator usually wins the race, and when he does not, he can use a reduced scale model of the transformer to be built and obtain the reactance by test, as described in a recent AIEE paper,[1] a procedure which may save time, and incidentally a professional reputation.

Figure 1. Cross section of windings



Mr. H. O. Stephens' method of resolving the reactance of nonuniform concentric windings into the concentric and interleaved components is a definite milestone in the art of reactance calculation and Messrs. H. B. Dwight and L. S. Dzung are to be congratulated on the very clear presentation, in the first part of their paper, of the physical phenomena justifying this method. At the risk of being accused of pedantry, I should like to call their attention, however, to an obvious oversight in their statement that I^2X is stored energy and is equal to the summation of $H^2/8\pi$. Being power, and not energy, I^2X cannot possibly be equal, but is proportional, to the summation of $H^2/8\pi$.

Having resolved the reactance of the transformer into its concentric and interleaved components, the next step is to select suitable formulas for calculating the two components separately. For the concentric component Dwight and Dzung use the well-known expression given by their equation 1. It will be observed that this formula does not take into account the curvature of windings and the presence of core iron, moreover, it assumes the effective axial length of windings to be equal to their physical length. The last two factors introduce errors of opposite signs, partly compensating one for the other, so that, as stated by the authors, the formula may be quite accurate, but only for a certain range of dimensions and proportions of the core and the windings.

For the interleaved component Dwight and Dzung use a formula based on the theory of geometric mean distances. The effects of curvature and of iron are again neglected. The reactance in question can be calculated with equal or greater ease, and with all the accuracy required for the purpose, by older and better known methods, of which that due to Rogowski[2] is perhaps the most advanced. The principal value of the second part of this paper is, therefore, in my opinion, not in the solution of this particular interleaved reactance but in the relative novelty of the method of attack. Although a rather complete study of the application of geometric mean distances to calculation of transformer reactances was published several years ago in German,[3] American technical literature seems to have neglected the subject.

Since the effect of curvature has been neglected in this paper in calculating both the concentric and the interleaved reactances, nothing would be sacrificed by performing the complete reactance calculation in terms of geometric mean distances. Figure 1 of this discussion represents the windings of the transformer investigated in the paper. Each winding is shown subdivided into five equal blocks. When operating on the 11,000-volt connection block 6 is idle.

Primary-to-secondary reactance of a transformer is given, in terms of geometric mean distances, by the following formula:

$$X_{P-S} = K \log \frac{R^2{}_{P-S}}{R_{P-P} R_{S-S}} \tag{1}$$

where

X_{P-S} = primary-to-secondary reactance
K = coefficient depending on frequency, the length of mean turn, the base of the log, and the choice of units
R = geometric mean distance between areas indicated by subscripts

For the present case the primary consists of blocks 1, 3, 5, 7, 9, the secondary of blocks 2, 4, 8, 10, so that equation 1 becomes:

$$X_{13579-24810} = K \log \frac{R^2{}_{13579-24810}}{R_{13579-13579}\, R_{24810-24810}}$$

$$= K \log \frac{R^{2\cdot5}_{13579-246810}\; R^{0\cdot4}_{13-24}}{R^{0\cdot3}_{579-6810} R_{13579-13579}\, R^{0\cdot5}_{24-24} R^{0\cdot5}_{24-8.0}} \tag{2}$$

Equation 2 contains only geometric mean distances between rectangles and from rectangles to themselves, all of which can be calculated by the method described in the paper. The point of particular interest in this solution is that the final reactance has been obtained directly, without resolving it into concentric and interleaved components.

If it is desired to retain the resolution of reactance into concentric and interleaved components, the concentric component can be readily calculated as follows. Let the primary, consisting of blocks 1, 3, 5, 7, 9, be called A and the secondary, consisting of blocks 2, 4, 6, 8, 10, be called C, so that equation 2 becomes:

$$X_{A-C} = K \log \frac{R^2{}_{A-C}}{R_{A-A}\; R_{C-C}} \tag{3}$$

Following the method described in the appendix to the paper and denoting the space between A and C by B:

$$X_{A-C} = K \log \left[\frac{R_{ABC-ABC}^{\frac{(a+b+c)^2}{ac}}\; R_{B-B}^{\frac{b^2}{ac}}}{R_{AB-AB}^{\frac{(a+b)^2}{ac}}\; R_{BC-BC}^{\frac{(b+c)^2}{ac}}\; R_{A-A}\; R_{C-C}} \right] \tag{4}$$

Finally, using natural logs and expressing geometric mean distances in terms of semiperimeters, equation 4 can be replaced by the approximate expression:

$$X_{A-C} = K_1 \left[\frac{\frac{a}{3} + b + \frac{c}{3}}{h} - \left(\frac{\frac{a}{2} + b + \frac{c}{2}}{h} \right)^2 \right] \tag{5}$$

For a wide range of proportions the approximate expression (5) gives a value within two per cent of the exact expression (4).

An interesting side light on H. O. Stephens' method may be obtained by substituting algebraically the values of concentric and interleaved reactances in terms of geometric mean distances, the former being given by equation 4, into the H. O. Stephens' formula:

$$X_{13579-24810} = X_{13579-246810} + \frac{1}{25} X_{24810-6} \tag{6}$$

If equation 6 were exact the result of this substitution would be equation 2. Actually, however, although a very close approximation, equation 6 is not exact. The exact formula is:

$$X_{13579-24810} = X_{13579-246810} + \frac{1}{20}(5X_{13579-246810} - 9X_{135-246} + 4X_{13-24}) +$$
$$\frac{1}{25} X_{24810-6} + \frac{1}{100}(X_{2-4} + 2X_{2-6} - 2X_{2-8} -$$
$$X_{2-10} - X_{1-3} - 2X_{1-5} + 2X_{1-7} + X_{1-9}) \tag{7}$$

Considering the difficulty of obtaining accurate reactance by tests on a model of the size described in the paper, the agreement between calculated and test values is satisfactory, even if inconclusive. It is regrettable, however, that the authors do not state whether in making their tests without an iron core they had the primary and secondary windings of equal turns and connected in series opposition, thus obtaining

$$X_{1-2} = \omega(L_1 + L_2 - 2M_{1-2}) \tag{8}$$

corresponding to the basis of their calculation. If in their tests they had the secondary short-circuited they were measuring:

$$X_{1-2} = \omega\left(L_1 - \frac{M^2{}_{1-2}}{L_2}\right) \tag{9}$$

Although (8) and (9) are practically identical for an iron core transformer, they may be radically different for an air core transformer.

References

1. Reactance and Stray Losses of Power Transformers, **H. L. Cole.** AIEE Transactions, 1934, page 338.

2. Mitteilungen ueber Forschungsarbeiten, **W. Rogowski,** 1909.

3. Weitere Entwicklung der allgemeinen Methode zur Berechnung der Streuung von Transformatoren, **G. Petrow.** *Electrotechnik und Maschinenbau*, 1934.

H. B. Dwight: In connection with the interesting discussion by A. N. Garin, a distinction may be made between expressions which are so long as to be of merely academic interest, and formulas which are concise enough to be of practical use. For instance, equation 2 of the discussion contains four geometric mean distances of one rectangle from another, and if these are to be calculated by the method described in the paper, each would give rise to several self geometric mean distances, making 13 self geometric mean distances for the formula. But equation 2 of the paper gives the reactance with only four self geometric mean distances, and so is not unduly long.

The observation is correct that I^2X is proportional to stored energy, not equal to it. The coils in the model ironless transformer had a turn ratio of one to one and were connected in series. The secondary was not short-circuited.

In the thesis work upon which the paper is based, the self- and mutual inductances were calculated, as a check, by formulas for cylindrical coils. This brought the curvature of the conductors into the calculation but not the effect of the iron core. It seems probable that such long calculations will not be practical for routine computations in designing. The need at the present time appears to be a comparison of the results of the shorter calculations with measurements on a number of practical transformers whose dimensions have been accurately found, so that the percentage error to be expected from a given calculation may be known.

L. S. Dzung: Rogowski's method of attacking the problem of reactance of interleaved transformer windings, as mentioned in Mr. A. N. Garin's interesting discussion, is very general in character; but the restriction[1] on dimension ratios of his approximate formula[2] limits its application more suitable to the calculation of the reactance of an interleaved transformer rather than to that of the interleaved component of a transformer. The coil shape of the former is usually such that the axial height is small compared to the radial depth. This condition is seldom realized in the case of the interleaved component of a transformer. His more exact formula[3] is too lengthy to be applied in practical designing.

It may be noted that the curves on figure 2 of the paper and the little formula printed beside offer a very simple means to a practical designer. Equation 2 of the paper and also equation 2 and equation 4 of Garin's discussion have the disadvantage that they involve obtaining a small number from the difference between large numbers. In preparing the curves logarithms have been taken to a sufficient number of significant figures so that the final results will give engineering accuracy.

Equation 4 of Garin's discussion, which is equation 9 of G. Petrow's paper in *Elektrotechnik und Maschinenbau*, 1934, has been used in the thesis to compare the reactance of the concentric component as calculated by the geometric-mean-distance method against that by the formulae for cylindrical coils and by the usual formula, equation 1 of this paper. The results of these three calculations are respectively 5.30 per cent, 5.31 per cent, and 6.21 per cent for the transformer given in example II of the paper.

The effect of the iron core can be taken care of by the method of image as indicated also in Petrow's paper. A comparison between equation 21′ and equation 23 of Rogowski's paper shows that this effect would not be very great

References

1. **W. Rogowski,** *Mitteilungen ueber Forschungsarbeiten.* Heft 71 (1909), Abs. II, §3, 2.

2. **W. Rogowski,** ibid., equation 23.

3. **W. Rogowski,** ibid., equations 13 and 14.

The catalytic effect of metals on oxidation as well as deterioration of the oil in the absence of oxygen has been referred to at several points in the paper. However, data has been given only for brass. It seems that similar data for the metals, which the cable saturant must contact, would be of greater interest and value. We would appreciate such data as the authors might be able to supply for such metals as copper, lead, tin, and iron.

The conclusions drawn by the authors upon the effects of oxidation cannot be applied to cable practice without further investigations. All the work has been done for relatively short time intervals: 192 hours is, after all, but a brief period in the expected life of a power cable. Almost none of the curves has approached a constant value of power factor in this length of time. It seems safe to assume that these curves will continue to rise for a much longer period of time, eventually, perhaps, to a value so high that successful cable operation might be impaired. It also seems possible that there may be some further later reaction of the oxidized products with themselves or with fresh oil, which may cause a more rapid increase of power factor. Certainly, definite conclusions should not be reached until the results of the authors have been substantiated by long time tests.

Moreover, these tests have been made under constant conditions of temperature and pressure, tending to discourage any movement of the oil through the samples. If the samples were subjected to load cycles similar to those of an operating cable, so that there would be an oil migration, permitting the oxidized products to encounter fresh oil, an entirely different set of results might be obtained.

We hope that Professor Whitehead will continue his work on this phase of cable saturants, so that these factors of time and oil migration may be considered.

Oil Oxidation in Impregnated Paper

Discussion and authors' closure of a paper by J. B. Whitehead and T. B. Jones published on pages 1492–1501 of volume 56, 1937, AIEE TRANSACTIONS (December 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the cables and research session of the winter convention, New York, N. Y., January 27, 1938.

L. E. Fogg and **R. B. Power** (Kennecott Wire and Cable Company, Phillipsdale, R. I.): About eight or ten years ago the research department of our company attempted some electrical tests on samples quite similar to those used by the authors. The results of this work were very unsatisfactory because of the nonuniform shrinkage of the paper samples. During the drying process, bulges and swills were formed in the samples to such an extent that the upper electrode was appreciably raised, even though its weight was sufficient to produce a pressure of several pounds per square inch on the sample. We would be interested to know if the authors encountered any such difficulty in their work, and how they were able to avoid it.

In connection with figure 7 of the paper, the authors suggested that a cause of the rising power factor—voltage characteristic might be the formation of some ions through atomic or electronic collisions. It is not obvious why such a factor should permit later flattening of the curves as still higher voltage stresses are applied, unless it may be assumed that there are but a limited number of atoms susceptible to such ionization. We would appreciate hearing the authors' viewpoint on this phase of the subject.

There is an apparent discrepancy in figures 22 and 23. The authors attribute to incomplete saturation both the low capacitance of figure 22 with respect to the comparable oxygen treated sample, and the initial decrease of the ionization curve of figure 23. However, this decrease apparently is brought about by more complete saturation, which at the same time should bring about an increase in the capacitance of figure 22, which increase is conspicuously absent.

L. J. Berberich (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The result reported by the authors that small amounts of oxygen had practically no effect on the electrical properties of the one oil studied throws new light on the oxidation problem of cable oils. Unfortunately, however, in order to generalize this result, a range of oils of different constitution must be studied. The authors give very little information which would enable one to obtain an idea of the constitution of the oil except for the broad statement that the oil is a "highly refined paraffinic cable oil." While there is no accurate way of characterizing the constitution of oil, it has, nevertheless, been found that the "viscosity index" is of value in this connection. This leads the writer to suggest that more use should be made of this index by those studying insulating oils.

The term "viscosity index" and its use as a constitutive property of the oil was first proposed by Dean and Davis (*Chem. and Met. Eng.*, volume 36, page 619, 1929). It is independent of the value of the viscosity and permits the expression of the viscosity-temperature coefficient of the oil as a simple function of the Saybolt universal viscosities at 100 and 210 degrees Fahrenheit. The system was devised on the basis that a typical coastal oil is taken to have a viscosity index of zero and a typical Pennsylvania oil is taken to have one of 100. From empirically derived equations connecting the viscosities at 100 and 210 degrees Fahrenheit for oils from these two extremes of crudes, Dean and Davis compute data for a table. Knowing the viscosities at 100 and 210 degrees Fahrenheit, use of this table and a simple arithmetic calculation will give the viscosity index.

A number of interesting correlations of viscosity index with other properties of insulating oils have already been made. Sommerman (ELECTRICAL ENGINEERING, volume 56, page 566, 1937) has found that the amount of x-wax formed by cable oils when subjected to gaseous ionization increase with increase in viscosity index of the oil. Balsbaugh, Larsen and Oncley (1937 Report on Research Project on Electrical Insulating Oils at MIT sponsored by Utilities Coordinated Research, Inc.) have found at least an approximate relationship between ease of oxidation and viscosity index among a group of oils representing extremely wide variations in constitution. Viscosity index heads the list of physical constitutive properties which these workers suggest as useful for predicting chemical behavior. The writer also, in his work on cable oils, whether it was a study of stability to oxidation or stability to gaseous ionization, has found the use of viscosity index valuable. Hence, with this much evidence in favor of viscosity index, the writer believes this work of the authors could be better correlated with that of others if the viscosity index had been given.

G. M. L. Sommerman (American Steel and Wire Company, Worcester, Mass.): From the physical properties of the oil given in table II by Whitehead and Jones, it is calculated that the specific gravity of the oil at 60 degrees Fahrenheit is $G = 0.918$ and the viscosity at 100 degrees Fahrenheit is $V = 2{,}360$ Saybolt seconds. These data may be used to calculate the viscosity-gravity constant of the oil according to the method proposed by J. B. Hill and H. B. Coats (*J. Ind. and Eng. Chem.*, volume 20, 1928, page 641), which is as follows:

$$a = \frac{10\,G - 1.0752\log(V - 38)}{10 - \log\,(V - 38)}$$

For the oil in question, $a = 0.84$; for highly paraffinic oils, $a = 0.80$; for highly naphthenic oils, $a = 0.87$. This indicates that the oil is probably of midcontinent source with a viscosity index in the neighborhood of 70. It would be of interest to have oxidation data of the kind presented by Whitehead and Jones for the other types of oils.

From the data presented in this paper it is not clearly proved that the *process* of oxidation in oil (as distinct from the results of oxidation) is a source of increased power factor. First, the decrease in power factor following the degassing of aged oil may be due to the removal of volatile oxidation products, as recognized by the authors. Second, the higher "ionization factors" of the undegassed samples compared with those of the degassed ones may also be due to volatile constituents. Third, the greater rate of rise of power factor with increase in temperature for specimens containing more oxygen may be due simply to the higher power factors of the more highly oxidized oils. Power factor-temperature curves of impregnated paper similar to the authors' figure 18 were reported by the writer in a recent paper (ELECTRICAL ENGINEERING, volume 56, 1937, page 566, figure 6). Rapidly rising power factor-temperature curves were obtained when the saturants were *degassed* deteriorated oils, and the values were practically independent of time, at least up to 24 hours. This is also in accordance with the results reported earlier by Whitehead (AIEE TRANSACTIONS, volume 52, 1933, page 667).

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): We in Chicago have been making tests on 1,000-foot lengths of experimental 132-kv cable and have obtained some test data on the effects of small amounts of dissolved oxygen or air on the characteristics of oil-filled cable insulation. Apparently during either manufacture or installation a slight amount of air was entrapped in some of these cables. After these cables had been subjected to heating cycles to about 70 degrees centigrade for 10 or 20 days, measurements of power factor at 60 degrees centigrade showed no change at all from the measurements obtained when the cables were first installed. In one cable the effects of the entrapped air required one month to show increases in power factors at 60 degrees centigrade, while for the other cable a few years were required.

From this experience and other considerations, I am forced to disagree with the conclusion of Whitehead and Jones on the relative unimportance of small amounts of oxygen as affecting electrical properties. Tests on this point apparently require more than the seven days used by them.

One of the outstanding characteristics of the deteriorated experimental cables in Chicago was the development of so-called negative ionization factors. The authors' tests obviously did not last long enough to develop negative ionization factors.

It is of interest to note that the ionization factors reported by the author decreased "when oxygen and volatile products were withdrawn." This fact seems to indicate that some gaseous ionization was present, and such a conclusion is supported by the test results with nitrogen.

The radial power-factor tests were made at room temperature. We have found that samples which show interesting variations in power factor when tested at 60 degrees centigrade show in some cases insignificant variations at room temperature.

One of the helpful results of the authors' studies is that, in testing stressed oil, it is better not to remove moisture and volatile products in order to retain reliable indications of the condition of the stressed oil.

J. B. Whitehead and **T. B. Jones:** We are in agreement with the suggestion of Doctor L. J. Berberich that it would be desirable to correlate all studies of the electrical properties of oils with the respective values of the viscosity index. In the case of the oil used in our studies, we did not determine the viscosity index, nor was it furnished with other properties of the oil as given by the refiner, as set forth in table 2. We note, however, that Doctor Sommerman in his discussion has estimated the value of the viscosity index to be in the neighborhood of 70.

Mr. Wyatt raises the question of the influence of a longer period of test on variations of layer power factor due to oxidation. We agree with him that longer tests would probably accentuate layer variations of power factor. However, our results indicate that the U-shaped curves sometimes observed in new cables are probably not due to oxidation. Furthermore, we have given evidence of a quantitative evaluation of the amount of oxygen necessary to produce a layer effect within a limited time.

Replying to Messrs. Fogg and Power, we encountered no instances of buckling or nonuniform shrinkage in our samples. Throughout our tests a constant weight was kept on the upper electrode. This was done to maintain uniform pressure throughout the test. Apparently this weight was sufficient to prevent troubles of the nature mentioned. A rising power factor-voltage characteristic passing through a maximum, and followed by a descending portion has often been noted in our work. An explanation has been offered in the paper "Residual Air and Moisture in Impregnated Paper Insulation—II" (Whitehead, Kouwenhoven, and Hamburger, AIEE TRANSACTIONS, volume 47, 1928). The conductivity and the number of ions in the oil have relatively low values. With increasing stress collision ionization is possible, but is not cumulative, owing to the limited length of path. Above a certain stress all of the free ions, including those caused by ionization, pass to the limits of their free paths in both positive and negative half cycles. A saturation condition results, the power factor passes through a maximum, and with further increase of voltage, conduction current is constant and capacitance current increases, causing a decrease in power factor. This picture is a suggestion only. An alternative one for the rising power factor at lower stresses is that with increasing stress large molecular aggregates surrounding the ions are stripped of their outer envelopes of neutral molecules, acquire higher velocities with resulting increased conductivity. The curves of figure 21 indicate that with increasing temperature both of these effects may be involved.

The apparent inconsistency between the power factor-voltage and power factor-time curves for nitrogen and for air is due to the difference in pressure (gas content) between the two tests. The nitrogen test was at ten centimeters and air test at one millimeter pressure. Thus in the nitrogen sample there was 100 times as much gas as in the air sample. Thus capacitance changes in the latter were too small to be detected. In this connection, it is worth noting that the constant value of capacitance of the air sample is between five per cent and ten per cent less than that of the one-millimeter oxygen sample, thus indicating a better impregnation for the latter.

We are glad to note Doctor Sommerman's computation of the viscosity index of the oil. We note also that he feels that our tests do not clearly prove that the process of oxidation is a cause for increased power factor. We agree to this, but on the other hand, we are not greatly impressed by the grounds of his doubt. What reasons has he for supposing that volatile products of themselves can cause an increase in power factor? The work of Piper in fact indicates that the addition of a wide variety of soluble oxidation products to an oil has little if any effect on power factor and loss. It seems to us that a far more probable and powerful cause is to be found in the continual process of chemical change during oxidation, and the temporary separation during this process of ions of opposite sign. If such is the case, increases in conductivity and power factor are logical.

We agree with Mr. Halperin and others that in any studies of the oxidation process long periods are desirable. He makes the mistake, however, of comparing the conditions of our tests with those of his longtime tests on completed cables. His tests contain a variety of factors and influences on power factor and stability that we have taken great care to eliminate. His succession of temperature cycles particularly, introduces the whole question of the creation of voids and the resulting gaseous ionization. Gas bubbles and voids and gaseous ionization in the ordinary sense were apparently entirely absent in our tests. In fact we find in the result of Mr. Halperin's tests a strong corroboration of our conclusion that oxygen in small amounts in impregnated paper insulation has little or no effect as a deteriorating agent. In particular we repeat that in our experiments a constant supply of oxygen was kept up, which is definitely not the case in a closed cable, and that in spite of this fact, oxygen to the extent of 0.013 per cent by volume in the oil has an effect on the oil which is not greater than that caused by contact alone with paper and with metals.

The Current-Carrying Capacity of Rubber-Insulated Conductors

Discussion and author's closure of a paper by S. J. Rosch published on pages 155–67 of this volume (March section), and presented for oral discussion at the cables and research session of the winter convention, New York, N. Y., January 27, 1938.

H. B. Dwight (Massachusetts Institute of Technology, Cambridge): In 1935 and 1936 some thesis investigations were made by C. R. Boytano, I. I. Hochberg, and B. R. Souza at Massachusetts Institute of Technology, under my supervision, on the current-carrying capacity of single-conductor, 600-volt, rubber-insulated, braid-covered conductors in three and one-half-inch fiber ducts encased in concrete. The duct line was 30 feet long, with three ducts. Two sizes of samples furnished by the Simplex Wire and Cable Company were tested, with the following results:

Over-all thermal ohms per foot of duct, from the copper to the outside of the concrete, with the copper at 40 degrees centigrade.

Size	Number in Duct	Thermal Ohms per Foot (Degrees Centigrade for One Watt per Foot of Duct)
Number 4/0	1	5.0
Number 4/0	2	3.8
Number 4/0	3	3.4
500,000 circular mils	1	4.9
500,000 circular mils	3	2.9

The thermal ohms are slightly less than the values given, for temperatures above 40 degrees centigrade for the copper.

These results for fiber duct are of course not directly comparable with those for iron conduit.

W. A. Del Mar (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): This is not merely another paper on "carrying capacity." It is the culmination of years of co-operative effort and research in which practically all who have studied the subject have had some voice. It should form the basis of future standard tables of carrying capacity and of future practice.

Mr. Rosch is to be congratulated on a fine piece of laboratory work and on his effective collaboration with other engineers in orienting his new data in relation to their data and experience.

D. W. Ver Planck (Yale University, New Haven, Conn.): The interesting paper by Mr. Rosch gives a much needed treatment of the subject of heat transfer from wires both in conduits and in the open. The study is based on the assumption that the heat transfer from the wires is entirely in the radial direction, as of course it is, for the major portion of any long uniform cable. One should not, however, lose sight of the fact that near the terminal of a cable there may be a considerable axial transfer of heat to or from the connected apparatus.

From the standpoint of this paper the case of greatest interest is where the connected apparatus tends to run hotter than the cable. This condition is encouraged by various apparatus standards which permit a maximum terminal rise of 30 degrees centigrade and in some cases even 40 degrees centigrade. Obviously, such rises above a 30 degree centigrade ambient will subject the end of the cable to temperatures from 10 degrees to 20 degrees centigrade in excess of the 50 degrees centigrade specified by Mr. Rosch as the limit for rubber insulation. It is the purpose of this discussion to indicate how great a length of the cable will be influenced by the high terminal temperature rise.

To derive the equation for axial temperature distribution let

x = distance along cable from terminal
T = temperature rise of copper at x
T_0 = temperature rise of terminal
q = heat generation per unit length
k = (radial) thermal conductance per unit length
R = (axial) thermal resistance per unit length

Upon applying the condition of heat balance to a differential length of the cable, there results the differential equation:

$$\frac{d^2t}{dx^2} - kRT = -Rq$$

Assuming that the length of cable extending from the terminal is great, the solution is:

$$T = \left(T_0 - \frac{q}{k}\right)\epsilon^{-\sqrt{kR}x} + \frac{q}{k}$$

indicating that the temperature rise decreases exponentially with distance along the cable from the terminal value T_0 to the value q/k which applies for conditions remote from the ends. A measure of the length to which the terminal temperature is propagated into the cable is $(kR)^{-1/2}$, a quantity which increases with cable size but in less than direct proportion. If the distance along the cable from one terminal to the next is not great, another solution taking account of both terminal conditions can be easily obtained.

Figure 1 of this discussion illustrates the use and checks the correctness of this analysis. A 4/0 cable in open air carrying 225 amperes is connected to a switch terminal having a rise of 35 degrees centigrade. The curve is calculated and the circled points are thermocouple measurements. The radial conductance per unit length k was deduced from Mr. Rosch's paper, table IV. The am-

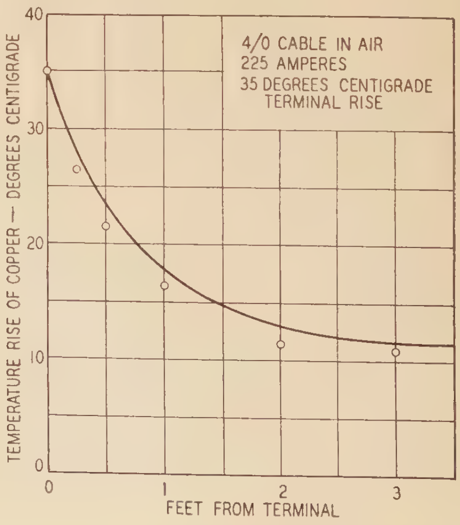


Figure 1

bient temperature was 25 degrees centigrade, and, while under these conditions the cable remote from the terminal attained a temperature of only about 36 degrees centigrade, a length of five or six inches near the terminal was subjected to temperatures in excess of the 50 degrees centigrade limit. Had the cable been worked to the limit calculated by Mr. Rosch's method, a still greater length would have been subjected to excess temperature, even though the safety factor included in curve *C* of figure 9 tends to reduce this length.

The possible overheating of the end portions of cables as a result of the high terminal rises permitted by various apparatus standards seems particularly worthy of consideration when it is remembered that these same end portions are likely to receive the greatest mechanical abuse during installation. It is hoped that the material in this discussion may help toward a better understanding of temperature conditions that sometimes exist near cable terminals.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): Rosch and those who worked with him are to be congratulated for giving us some valuable information on rubber-insulated conductors. The data presented, however, are not convincing that code rubber will have a long life when operating at 50 degrees centigrade. In their tests at 50 degrees centigrade the physical properties decreased. Perhaps the author is relying on the load in service actually being usually less than the rated load, or on the ambient temperature being less than 30 degrees centigrade most of the time.

In connection with building wiring, it seems to me that more thought should be given by the industry to the use of better grades of rubber instead of Code rubber, especially where there are possibilities of loading near the ratings or of high ambient temperatures. I have heard of some buildings where the rubber on the circuits was even two steps better in quality than Code rubber. The additional cost for a better grade of rubber insulation is small, especially in proportion to the total installed cost of a wiring installation, while the life of a wiring installation is on the average sharply increased by the use of better rubber.

It is interesting to note in figures 3, 4, and 5 that the rubber from the number 0000 cable stood up better than the rubber from the number 14 and number 16 wires. It would be interesting to know the author's explanation.

Referring to figure 9, which shows that the surface resistivity increases for cable diameters up to one and three-fourths inches, we have in the Commonwealth Edison Company been using a similar characteristic in resistivity for about ten years. Our curve is based on test data obtained for us by Barenscher at the University of Wisconsin. The curve is convex upward and has a resistivity of 400 for zero cable diameter, which becomes a value of 1,200 at two and one-half inches cable diameter. Mention of our curve has been made in the NELA meetings and in C. A. Bauer's article presented at the Great Lakes Section of the NELA underground systems committee on April 10, 1931 (Published in "1930–31 Report of Engineering Section," Great Lakes Division, NELA, Appendix XXXV, page 237). Our values are somewhat lower for the smaller cables than shown.

It would be of interest to know why the author plotted on figure 9, apparently, data from table VII instead of from table IV of his paper, because the latter data would result in a lower resistivity and a lower curve.

In contrast to the author's proposal to use the total area of two or three cables in a duct in connection with thermal resistivity, we have tried to take some recognition of the fact that the surface in the center of the combination of cables does not radiate heat. As a result, we have worked out a term for thermal resistivity for three cables based on two and one-fourth times the surface of one cable, the corresponding term being 1.83 in the case of two cables.

R. J. Wiseman (The Okonite-Callender Cable Company, Inc., Passaic, N. J.): Every engineer who has had occasion to compute the current-carrying capacity of rubber-insulated conductors installed in conduits has been puzzled by the difficulty of checking his calculations with the National Electrical Code. The other discussers have brought out the valuable work done by Mr. Rosch and his associates for the NEMA rubber covered building wire technical committee and we cable manufacturers are very grateful for the clearing up of many of the questionable constants such as radiation from braids and conduits of various sizes. To me, the real value to the paper comes from our ability now to be more certain of our calculations and the opportunity of revising the NEC so as to properly rate cables when drawn into conduits whether or not a single cable or several cables are used. Heretofore it was difficult to convince an electrical contractor or some utility engineers that the Code at the present time does not specifically state the current loading tables are for a single cable in a conduit. We are hoping that the Code tables will be revised and that they will give loadings for both single cables and three cables in a conduit such as table XI of Mr. Rosch's paper.

S. J. Rosch: Professor Ver Planck's comments with regards to the axial transfer of heat from connected apparatus to the terminating end of a cable, are very timely and to the point. This is a feature which has received very little consideration in the past and we recommend a study of his discussion by all those who are engaged in considering the question of heating of wiring in panelboards, circuit protection and the uniform current rating of service equipment.

Mr. Halperin questions the life of Code-grade rubber insulation at 50 degrees centigrade. As stated in the text, the investigation at 50 degrees centigrade was conducted on samples of cable submitted by eleven manufacturers. Figures 4 and 5 were chosen as typical of the extremes in performance when aged at 50 degrees centigrade. A study of figure 4 indicates that the trend is definitely parallel to the horizontal axis. This was true even when the aging was extended over a period of 19 weeks. From this it was felt that 50 degrees centigrade would give satisfactory life for Code-grade rubber insulations. Although space limitations prevented giving the performance data for the other nine manufacturers' products, it can be stated that they all showed the same trend as shown in figure 4.

We sympathize with Mr. Halperin's views on the desirability of using better grades of rubber insulation than the minimum grade now required by the National Electric Code. That the tendency is definitely in that direction can be seen from the fact that the Federal Specification Bureau's Specifications *JC* 106 and *JC* 121 now require a superaging type of rubber insulation for use on all wiring in projects under Federal supervision. This same type of insulation is also being considered by suitable committees in NEMA, IPCEA, and the ASTM subcommittee on rubber insulated wire and cable specifications. The National Electric Code has recently appointed a committee to study the trends in higher grades of rubber insulation, as well as other insulations which are capable of higher operating temperatures and possibly increased current ratings.

Regarding Mr. Halperin's question as to the reason why the physical aging of the 4/0 cables showed up better than the smaller sizes, we can only assume that this was a coincidence for manufacturers *A* and *B*. Had we given the data for the other nine manufacturers, it would have been seen that in six of the cases, the 4/0 cables showed up poorer than the smaller sizes.

As regards Mr. Halperin's questions on the values of B_b, the values plotted in figure 9 are the average values for B_b given in table IV and, since they are the average, they are more truly representative. The values given in table VII are for one condition only, namely, "horizontal open," and may be found under this column in table IV. During the computation of our results, we also used the areas suggested by Mr. Halperin, but they resulted in values for B_b that could not be fitted to a curve. It can also be readily seen that to use the areas suggested by Mr. Halperin, would result in more complicated formulas. Furthermore, so long as the "total" area is used in the computation of B_b and in the ultimate calculation of current-carrying capacity, no error is introduced in the result.

We appreciate the references given by Mr. Halperin concerning the values of *B* used by his company. We calculated several values of *B* from the data presented in Mr. Bauer's paper and found that on plotting them in figure 9, they practically fitted on curve *C*, the curve adopted for standardization. What is more surprising, however, is the fact that a curve plotted from the data presented by Mr. Bauer, almost completely parallels our curve *B*. It is regrettable that the factual data on which Mr. Bauer's formula for *B* is based was not given in his paper.

The comments of Professor Dwight are of interest, even though the data is not directly comparable to that obtained with iron conduit. They do, however, afford the author an opportunity to express his deep appreciation for the very excellent work done by Mr. C. R. Boytano, mentioned in Professor Dwight's comments. Mr. Boytano was responsible for the investigation of the thermal surface resistivity under the very able supervision of Messrs. A. C. Connell and B. Jore.

We also appreciate the kind remarks of Mr. W. A. Del Mar and Doctor R. J. Wiseman. The author was extremely fortunate in being able to discuss his results with the leading cable engineers in NEMA and the IPCEA. The present paper represents the combined engineering thought and effort of the wire and cable industry and, in conclusion, the author wishes once more to express his sincere appreciation to all those whose efforts were instrumental in making this paper possible.

Mechanical Uniformity of Paper-Insulated Cables

Discussion and authors' closure of a paper by K. S. Wyatt, D. L. Smart, and J. M. Reynar published on pages 141–54 of this volume (March section) and presented for oral discussion at the cables and research session of the winter convention, New York, N. Y., January 27, 1938.

W. A. Del Mar (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): Once again we are indebted to the Detroit Edison Company engineers for useful tools to assist in cable research. They have given us the radial power factor test, the hydrophil test, and now they give us the torsional penetrometer and the styrene wafer. We manufacturers are grateful for these means to assist us in giving to the industry the best cable that science and skill can produce.

The authors are undoubtedly right in looking for improvement in cable performance by the perfecting of mechanical uniformity. This goal has been the aim of cable manufacturers for many years, as evidenced by the improvements in taping and cabling machines, the use of caterpillar take-offs, pre-spiralled sectors, humidity control, and so forth. I doubt whether the styrene wafer will add anything to the knowledge which is the basis of these developments. So far, the styrene wafer has revealed nothing of that kind which was not known to the machine designers.

It is rather in more fundamental research that the styrene wafer will prove its usefulness. It has shown, for instance, that the paper tapes are practically tangential to round strands, thereby substantiating one of the claims made for the compact type of conductor, and it has definitely revealed the voids created by load cycles, both of which features in the past have been obscured by burring of the paper in cutting sections.

The number of inherent insulation failures in cables is now very small. If totally eliminated, the effect on the total outages would scarcely be noticed. If we leave out failures due to improper design of vertical cable ends, it is probable that a large proportion of the very small residual total of inherent insulation failures would be found to be due to unavoidable defects caused by the inherent fallibility of men and machines, rather than to any general condition susceptible of discovery by means of wafers. This is not to be interpreted as meaning that, in my opinion, cables are not susceptible of improvement. We shall have thinner walls, greater dielectric strength, greater power-factor stability, better sheaths, and many other improvements. I merely say that such improvements in mechanical structure of insulation as may be made in the future, will not materially reduce outages of cable.

It is, of course, in three-conductor, and particularly sector cables, that there is the most room for mechanical improvement, but life tests show that these cables are surprisingly close in quality to the single-conductor cables. Furthermore, the most carefully made laboratory-built cables are just as variable in their performance in load cycle tests, as the ordinary factory-built cables.

Inventors, realizing this condition, have sought to extend the voltage limits of cable, not by insisting upon impossible perfection, but by the more practical plan of accepting imperfections as inevitable and devising means to make them harmless. Thus Emanueli covers a multitude of sins by using a thin oil that maintains perfect impregnation, and both Bennett and Hochstadter effect the same result by putting the insulation under pressure. It seems to me that the authors of this paper are like people who insist on geometrically plane roads for safe and comfortable motoring, while others, like myself, prefer to have good tires, knowning that occasional road bumps are inevitable.

Referring to the curves of tape tension, the authors assume that uniformly high tension is the desideratum. It is not clear why they should hold this view as no evidence is given to support it.

I have seen cables with the most visibly nonuniform tape tension, that were perfectly satisfactory, and uniformly tight cables that failed. The tension of tapes is not a matter that can be considered by itself; the best tensions are tied up with manufacturing equipment and procedures, bending tests, oil viscosity, and operating temperatures.

We shall be better equipped to study this subject with the new tools the authors have given us, but it will take time to reach sound conclusions with them.

If the wafer method is to prove of great value, it will have to be greatly simplified, preferably along lines of inspection by reflected, rather than transmitted light, so as to eliminate the time and effort expended on making thin cuts.

The authors' study of tape staggering, is very much along the lines of a study I made in February 1930. Quoting from the unpublished report of that work:

> "Twelve cases have been considered with staggerings in stages of $^{1}/_{32}$ inch from cable *A* with tapes staggered the maximum amount to cable *K*, with tapes staggered the minimum amount. . . . It will be noted that they differ in two respects:
>
> 1. The recurrence of superimposed channels.
>
> 2. The length of the leakage path from conductor to sheath assuming the channels ionized.
>
> "The recurrence of superimposed channels weakens the cable to radial stresses and a short leakage path weakens it to tangential stresses. Thus there are two potential paths of failure in parallel and on voltage-time test, the cable will fail along the weaker one."

A summary of the study of these cables follows:

The radial dielectric path is about 50 times as strong as the tangential path. Hence to compare these cables, we divide the length of the tangential path by 50 and compare it with the paper

Table I

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Overlay†		Superimposed Radial Channels*		Shortest Leakage Path**	
Cable	32d's Inch	Per Cent	Per Cent	Mils of Paper	32d's Inch	Mils ÷ 50
A	10	43	50	110	430	269
B	9	39	14	189	429	268
C	8	35	20	176	386	242
D	7	30	33	147	343	215
E	6	26	10	198	300	187
F	5	22	25	165	257	161
G	4	17	11	196	214	134
H	3	13	17	183	171	107
I	2	9	12	192	128	80
J	1	4	9	200	85	53
K	0	0	4	210	0	0

* This includes channels with edges aligned, as well as those squarely superimposed.

** Paper thickness neglected.

† Tape is assumed $^{22}/_{32}$ inch wide, with $^{1}/_{32}$ inch gap, so that maximum possible overlay is $^{10}/_{32}$ inch or $\frac{10 \times 100}{23} = 43^{1}/_{2}$ per cent. The per cent overlays are rounded to the nearest integer.

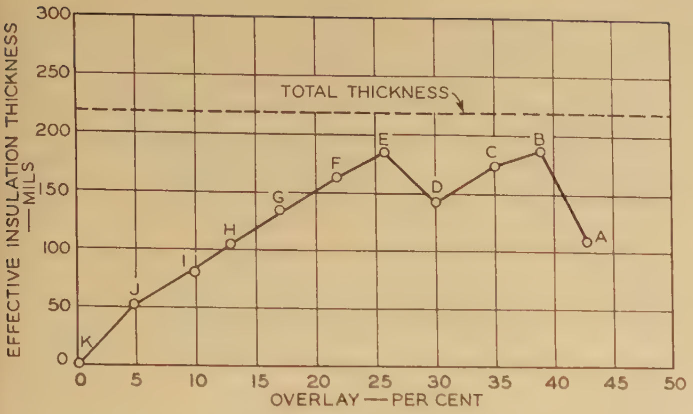


Figure 1

thickness of the radial path, as in columns 7 and 5 of the accompanying table I.

If we plot the lesser of these thicknesses (from columns 5 or 7) against overlay (column 3), we obtain the curve shown in figure 1 of this discussion from which it will be noted that there are substantially equal peaks at 26 per cent and 39 per cent overlay. The 26 per cent peak, however, gives better results due to the better bending characteristics of the cable.

Attempts were made to check curve *A* by voltage-time tests on specially made cable samples and while cables coming under the classifications of *A*, *H*, *I*, *J*, and *K* were definitely poor and cables *G* to *B*, definitely good, it was not possible to correlate the latter with the curve in figure 1, although the general trend was toward a maximum dielectric strength at *E* and *F*, rather than at *B*.

H. B. Dwight (Massachusetts Institute of Technology, Cambridge): May I ask if the mechanical tests described, particularly the test by making thin wafers showing the cross section, have been applied to large generator coils, and has information of interest been obtained?

R. J. Wiseman (The Okonite-Callender Cable Company, Inc., Passaic, N. J.): This paper again reports to us the valuable research work being carried out by the Detroit Edison Company in their desire to bring to our attention, tools or test methods which may be of help in our desire to improve the quality of our cables. However, in reporting the results of these test methods and the conclusions to be drawn from them, one must go slowly and cautiously because it is necessary to consider all the whys or wherefores that certain things are done, which ordinarily may be considered as a defect or shortcoming. For example: let us take the penetrometer and torsion tests which are supposed to indicate the degree of hardness tightness, or firmness of the insulation and the opinion is expressed that we should get a straight line plot of depth of penetration (figure 7) across the insulation. I am not so sure that we should get the same value for across the insulation. Perhaps a decreasing value as we go from the conductor outward or even an increasing value is better. We know in the taping operation that we have to adjust our tensions to prevent pinching or wrinkling of the inner tapes. Do we want a tightly wrapped cable which means a low value for penetration? If we do, we will get very little oil between the layers of the paper and this is as essential to us as oil in the paper itself is necessary if we hope to get good electrical characteristics. If too tightly wrapped we will not get good oil movement radially. If the paper is to loosely wrapped we will get drainage and voids. Therefore, we look for that wrapping which will give a well and uniformly saturated cable possessing low original ionization and high dielectric strength.

The development of the cable wafer is going to be very helpful to the cable manufacturer, as it gives him another tool for checking the mechanical setup of the cable. Here also, we must be careful about interpreting results. It does not necessarily follow that "comet's tails" unless distinctly more pronounced on one side than the other are due to the twisting of the conductor. There really is a comet's tail on both sides in the filler space. It can be due to the shape of the insulated conductor. A round conductor would show a longer comet's tail than a sector-shaped conductor. Also, it can be due to the use of too much filler material in order to get compactness and some of the filler will ride over the back of the conductor. If there is filler material between the conductors it is also due to too much filler and being forced into the space between the conductors. This is not serious as the filler is under high compression caused by the cabling operation.

Sometimes I wonder if we want the mechanical perfection that we hear about. We start with a good mechanical make-up in the factory and then as the authors say, we reel and unreel it, draw it into a duct, shape the ends around the manhole for splicing and finally it goes through the expansion and contraction due to loading. We upset the position of the papers and the oil moves but not entirely reversibly as in the case of oil-filled cables. If the tapes are wrapped tightly, we have a small amount of oil between layers. If too loose, we get drainage and poor electrical characteristics. If longitudinal movement of the cable is retarded, we get a forced radial expansion of the insulated conductors which will injure the insulation. A great deal is dependent on how a cable is handled and installed; in other words, the utility also has a responsibility where the cable leaves the factory in a good mechanical condition.

The oval type of cable overcomes some of the operating effects, but not installation. With this shape of conductor we get the paper along the minor axis stretching the necessary amount to take up the expansion of the oil and on cooling, forces the oil back again, thereby maintaining uniform saturation all the time. We also are able to hold down the internal pressure which develops during heating as well as prevent the cable from going to a high vacuum on cooling.

I am not able to go along with the idea that pretwisting of the conductors will eliminate the cabling problem. Figure 5, which is taken as an example of uniform insulation, does not have pretwisted conductors. We have made cables both ways and find it is not necessary to pretwist.

In taping, we not only look for the longest leakage path from conductor to sheath, but also the most effective use of layers of paper free of gaps. According to the table on page 151, one gets the impression that a 50-50 overlay is best. It is the worst, because we have only half the number of layers of paper effective due to the gaps lining up across the insulation. A 35–65 overlay is, on the average, about the best.

Let us not get the impression from the pictures shown in the paper that the cable manufacturers are sadly deficient in their ability to put out a quality product. If we did, the utilities would not be able to carry the loads at the voltages they do today and instead of the inherent failures of cables due to insulation being about ten per cent of the total failures, they might easily be over 50 per cent. We are constantly striving for both mechanical and electrical perfection, but there is an economic limit we can go to in view of the type of cable and how it is used. The chances of a large reduction in wall thickness are not promising in the near future.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): I ended my study of this interesting paper with mixed feelings and, as a result, my position is somewhat between that of the authors and that of some of the discussers. As usual and as indicated in the paper, we have co-operated and we have for several months been carrying on investigations as the result of the information first brought to our attention last spring by Mr. Wyatt.

The new tools developed by the authors are being used by many manufacturers and some utilities and should be of material assistance in improving the quality of paper-insulated cables. It remains to be seen, however, whether the use of such tools will eventually make feasible the radical reductions in the thicknesses of insulation of solid-type cables as prophesied by the authors. I will have to admit that as far as belted-type three-conductor 13-kv cable and single-conductor 69-kv solid-type cable are concerned, I do not see how improvements in the mechanical uniformity of the insulation will alone result in reductions in insulation thickness such as 30 or 40 per cent as implied by the authors.

Even though the failures due to insulation in cables made in the past 10 or 12 years are small in proportion to the total failures in underground systems, I do not agree with the implication of the remarks of one of the other discussers that there is practically nothing much more to be done as far as the insulation is concerned. There is still present the economic pressure to reduce costs, and one of the important ways of accomplishing this is to reduce the insulation thickness with safety.

As to the statement in the third paragraph of the introduction that one finds little or no information in the literature concerning compactness and uniformity of layer structure of insulation, I should like to point out that there was a tremendous amount of correspondence and oral discussion in the industry on the mechanical properties of insulation some 12 or 15 years ago. As a result, the American manufacturers practically eliminated the severe wrinkles of the insulation of multiple-conductor cables with sector-shaped conductors and the improper registrations of several tapes one on top of another. From time to time they have made further improvements in mechanical uniformity and I know of two important changes started in 1936. In addition, there are still arguments as to just how the tension and compactness of insulation should be. These tools of the authors should help settle these arguments.

There seems to be an idea in the paper that the effectiveness of insulation is reduced in exact proportion to the number of gaps that are in a straight line between any two electrodes. This implication is unwarranted.

As a general proposition, improvements in mechanical uniformity should apparently be of most benefit for three-conductor solid-type shielded cable with sector-shaped conductors and rated at 25 or 35 kv, the benefits decreasing down to the least possible benefit with oil-filled single-conductor cable.

C. L. Dawes (Harvard University, Cambridge, Mass.): The authors describe a process in which the paper tapes and the fillers of impregnated-paper cables become solidly embedded in their natural positions in transparent glass-like styrene. Thin cross sections or wafers permit a visual study of the mechanical structure of the cable, showing clearly any wrinkles, voids, butt spaces and the like which may be present. This process which involves in a high degree both chemical and physical technique gives engineers another method by which to eliminate the factors which are responsible for the all too frequent cable failures. The authors should be complimented on their important contribution to the art.

From many observations of cables subject to service conditions and accelerated life tests, I am in agreement with the authors' conclusion that the presence of voids, whether due to loose wrapping of the tapes or to butt spaces, does reduce materially the dielectric strength of the cable. With the expansion of the cable such as is caused by load cycles, the compound will tend first to vacate the voids because of the lack of capillary action existing in them. A very small amount of incipient ionization immediately produces mechanical impact which further drives the compounds from the voids, thus accentuating their effect. Not only is the potential drop across the voids reduced as stated by the authors, but also longitudinal stresses along the tapes in the neighborhood of the butts are developed. This is due to the fact that the voltage across a butt space is lower than that across the adjacent tapes, causing a voltage difference along the surface of the tapes, and possibly producing longitudinal creepage currents resulting in tacking and coring. (See C. L. Dawes and P. H. Humphries, "Ionization Studies in Paper-Insulated Cables, III," AIEE TRANSACTIONS, 1930, page 766.) This effect would be accentuated where two or more butt spaces are practically superposed, such as is shown in several instances in figure 14. As the authors state, when better precision in applying the tapes is attained, reductions in the thickness of insulation become possible without diminution in dielectric strength.

Investigation has shown that in many cases the thickness of the voids must be extremely small, for the voltage gradients at which ionization begins may be four or five times the ordinary critical gradient for air at atmospheric pressure. As early as 1919 Clark and Shanklin conducted a comprehensive investigation of this phenomenon in cables (AIEE TRANSACTIONS, 1919, page 489), and Dubsky studied the matter for insulations in general (AIEE TRANSACTIONS, 1919, page 537). My own investigations of a number of cables also show such high gradients with correspondingly very thin voids. These cables were never longer than 15 feet, inclusive of guards, so that the internal pressure could not have been far from atmospheric.

Table II

Cable Identification Number	Conductor (Thousands of Circular Mils)	Insulation Thickness (64th Inch)	Insulation	Dielectric Constant	Ionization: Actual Kilovolts	Ionization: Volts per Mil at Conductor: Insulation	Ionization: Volts per Mil at Conductor: Void	Estimated Voids Thickness (Mils)
1	500	16	Wood paper Compound	2.96	16.0	82.1	243	3.5
2	500	24	Manila paper Compound	2.96	21.0	78.9	234	3.7
12	500	16	Manila paper Compound	3.36	11.5	59.0	198	5.1
17	300	12	Wood paper Compound	3.24	7.0	47.3	154	7.1
19	300	12	Wood paper Compound	3.49	10.0	63.0	237	3.6
22	600	12	Wood paper Compound	3.20	12.5	79.6	255	3.1
24	600	12	Wood paper Oil	3.46	10.0	63.7	221	4.4

We also found that when impregnating compound was present in the voids, the gradient for initial ionization was practically double that with air alone (see Report of the Committee on Electrical Insulation, National Research Council, 1935, page 26). This increase in dielectric strength is apparently due to the presence of the vapors from the compound. There are little data on the dielectric strength of vapors under the conditions existing within impregnated-paper cable insulation. However, in J. J. Thomson's "Conduction of Electricity Through Gases," volume II, third edition, page 510, a table taken from the data of Bouty shows the dielectric strength of certain organic vapors. The data were obtained at pressures of from 0.0055 to 2 centimeters of mercury, which pressures are much lower than those ordinarily existing within cable insulation. The table does, however, show that the dielectric strength of such vapors is much greater than that of air alone, which confirms our experiments.

In the accompanying table II are a few typical data obtained with actual cables, some of which were new and others which had been in actual service. The estimated thicknesses of the voids were based on the available data for air, since no data for vapor-filled voids, particularly petroleum, of these small thicknesses and also at atmospheric pressure are available. It is very probable that many of the voids are thicker than estimated due to the presence of the vapors.

W. F. Davidson (Consolidated Edison Company of New York, Inc., Brooklyn, N. Y.): It was my good fortune to have followed, from their inception, the studies reported in this paper and I like to think that some of my words of encouragement were a factor in bringing them to a successful conclusion. Lack of factual information is a complete barrier to full engineering development. In the field of cables we have been seriously handicapped by not having exact knowledge of the inner mechanical structure of cables. Now at last it is possible for the cable designer to study the effects of various details of the manufacturing process and the user can determine the effects of installation and operating conditions; it is no longer necessary to guess as to the effects of many of these factors.

When we turn to the authors' interpretation of some of their observations, I am not able to agree with all that they have said. For cables of the 24-kv class, which form the basis for many of the comments, it seems to me that the ill effects of ionization and leakage path have been somewhat overemphasized. Care must be taken lest we allow ourselves to pay too much attention to correcting these defects at the expense of other equally important details. Much progress has been made in improving the quality of insulation but the results, as measured by cable investment, are none too encouraging. One of the most important problems facing the cable engineer during the next few years is reducing costs. To me the only hope of accomplishing this lies in finding ways and means for operating cables at higher temperatures and with a greater range of temperatures. The designer must not be unduly handicapped in his efforts to accomplish this end.

C. J. Beaver (nonmember; W. T. Glover and Company, Ltd., Manchester, England): It is agreed by the authors, and may therefore be postulated for the purpose of the following notes that

(*a*) Ionization is practically the only inherent cause of failure in a reasonably well made dielectric.

(*b*) Ionization conditions are developed in cable dielectrics by physical processes incident to the use or working of the cable.

(*c*) The physical properties of the (solid type) dielectric are deficient for the purpose of preventing such development.

It follows that under reasonable working conditions the electrical life of the dielectric is dependent on its physical properties, and consequently the main question arising from the paper is as to the relative contribution of some lack of mechanical uniformity to the sum total of deficiency in physical properties.

In a solid-type lead-sheathed dielectric subjected to cyclical temperature changes, it is evident that at any temperature below the maximum, gaseous spaces (voids) must exist in the dielectric. The electrical stressing at which ionization will commence in these spaces will vary roughly inversely as the space dimension in the direction of the electric field, for a given set of conditions such as gaseous pressure, type of gas, and so forth.

Thus it is obvious that in a radially stressed solid-type dielectric, the most vulnerable gaseous spaces (voids) will occur in the butt spaces between the edges of adjacent laps of paper, where the radial dimension of the space will be equal to that of the paper thickness.

It is difficult to conceive a dielectric so poor in a mechanical sense that larger radial dimensioned spaces can exist between radially adjacent papers.

Hence it is clear that the stress at which ionization initiates depends on the butt space conditions, and it is this stress which controls the asymptotic or long-life voltage value of the dielectric.

The importance of the length and condition of the leakage paths (zigzag and step) appears to have been highly overemphasized in the paper.

The lengths of these paths and also the physical conditions existing between radially adjacent paper surfaces, do not affect the asymptotic or long-life voltage value of the dielectric, but merely influence the shape of the time-voltage curve above the asymptotic voltage value.

The Robinson theory confirms this as quoted by the authors on page 13: "Tracking along paper surfaces, which is now coming to be accepted as the mechanism of ionization failure, after a core has formed. . . ."

After load cycle testing there will be a general slackness or lack of mechanical pressure between papers in a radial direction, owing to the action of the radial flow of impregnating oil in a zigzag manner between the paper surfaces during the temperature changes.

Although a wafer of such a cable before and after the load cycles shows this difference, the increase in ionization in the latter sample will occur chiefly in the voids in the butt spaces caused by the process of oil expansion and lead sheath distension in an initially well-impregnated dielectric.

It has been proved by the writer in a very comprehensive series of experiments during the development of the gas filled cable (Paper No. 204, "The Gas Filled Cable," C.I.G.R.E. Session 1937, Paris) that electric failure of a cable dielectric invariably occurs through, and initiates in a butt space, and is also dependent on the butt-space thickness.

Under these conditions the most important dielectric feature which should be taken care of in the manufacturing processes is the avoidance of registrations between radially adjacent butt spaces, so that the space dimensions never exceed a single paper thickness.

In this connection special lapping machines (British Patent No. 182,510) are used by a British firm in which the cable is revolved, while the papering heads carrying the paper strip spools are stationary. The paper strips pass through slots in a sheet metal framework fixed to the machine, thus ensuring at all times that each paper strip is applied to the cable at a definite longitudinal position with respect to the adjacent papers. These arrangements also provide easy means of ensuring uniform tension of application of the paper strips.

It may be mentioned that the strips are preimpregnated, so that no question arises as to "conditioning" of the paper, nor of shrinkage wrinkling or other deficiencies arising in the manner referred to in the paper.

There is one other important point which should be watched in the manufacturing process and that is, that the mechanical structure of the cable dielectric should be such that the paper strips are not torn or cracked through during bending of the cable, so that large-radial-dimensioned gaseous spaces are avoided.

In this connection it is very desirable to avoid a 50 per cent overlap owing to the tendency of the paper between two alternate butt spaces to be cracked, and to become torn in consequence.

The authors do not appear to have considered this aspect, which in actual practice—from the installation point of view—is very important.

The authors' extreme optimism for future improvements and cost reduction in solid-type high-voltage cable is in direct conflict with present-day knowledge of the limitations of such dielectrics.

No amount of control of mechanical uniformity of cable manufacture can alter the stark physical facts that in a lead-sheathed cable subjected to temperature cycles, voids or gaseous spaces equal in volume to the oil expansion must exist at the low temperatures, and that the most vulnerable spaces will form in the butt spaces where the radial thickness of void is at a maximum.

The stress rating limitation of the modern solid-type cable dielectric depends upon the following factors:

1. The radial thickness of the butt spaces in turn dependent upon the minimum thickness of paper which it is feasible to use.
2. The maximum temperature to which the cable may be heated.

The above two factors affect directly the intensity of ionization in the butt spaces and set the limit to the permissible stressing, and conversely the loading.

A comparatively slight improvement in the homogeneity or uniformity of a dielectric cannot cancel out the whole physical problem entailed by the lack of reversibility of expansion and contraction effects, leading to ionization; and in face of the well-known necessity of restricting the temperature factor at even 60 kv it would appear quixotic to pursue working voltages up to 100 kv (as mentioned by the authors) with solid-type cable.

The scientific (and commercial) solution of the problem lies in the direction of the abolition of ionization in the dielectric, for example, on the lines of the "gas filled" cable (referred to hereinbefore), in which, without external compensating devices, and without restriction of loading temperature, ionization is completely suppressed to any designed extent, for instance, up to twice working voltage.

The authors' desiderata regarding reduction of insulation thickness and increased duct loading should be much more easily attainable along this line of development in which all constructional factors are capable of being definitely designed, and behavior in use is automatically controlled by reason of the reversible physical properties of the dielectric, preventing any permanent change (leading to ionization) under any working condition of the cable.

C. H. Jolin (nonmember; Merz and McLellan, Newcastle-on-Tyne, England): The description of methods used to investigate the mechanical construction of paper-insulated cables are very interesting. The three mechanical methods, "penetrometer," "push-out," and "torsion" are somewhat crude, in particular, the push-out method where the force required, besides varying with the tightness of the paper, will also depend on the roughness of the paper surface and the consistency of the impregnating compound. The torsion method seems to be useful but it would be an advantage if an illustration could be given of the instrument used.

The wafer method is, I think, the best but it would appear necessary for this test to be carried out by skilled operators in a laboratory and under these conditions it should prove one of the most useful tests devised up to the present time. I think that the test will prove of most value to manufacturers as they will have the necessary facilities for making the tests, from the results of which they will be able to determine the effects of different methods of manufacture.

I gather from the paper that the author is in favor of the insulating space of the cable containing as large a proportion of paper to oil as is possible consistent with the cable being able to pass a reasonable bending test. I am in agreement with this for normal type of cable as it must assist in avoiding trouble due to compound expansion.

This requirement is not so important in other types of cable, for instance oil-filled cable is so designed that any gaps between papers will always be filled with oil and will, therefore, be harmless but even with this type of cable the smaller the amount of oil in the insulation, the smaller the oil reservoir capacity required to allow for oil expansion.

The gas pressure cable is in a different category as in some designs definite gaps are left between papers to allow free access of the gas under pressure to all parts of the insulation.

The author states that it should be possible to so improve the dielectric of the solid cable that it would be suitable for use at 100 kv or over.

I should like to know whether the author would recommend using solid cable at the same maximum dielectric stresses and temperature as is now used for oil-filled and gas pressure cable.

It appears to me that however well the cable is manufactured, some disturbance of the insulation will take place due to reeling and unreeling the cable on drums and handling the cable during installation. The spaces caused by these disturbances will remain in the solid-type cable whereas such spaces in the oil-filled cable and the gas pressure cable would be filled with oil or gas under pressure respectively and would thus be harmless. It would therefore appear that theoretically the oil-filled and gas pressure cables will be better than the solid type.

The illustrations accompanying the paper are interesting and show that delta-shaped-conductor three-core cable cannot be so satisfactorily insulated as a cable with circular conductors. The cable illustrated in figure 6 is so bad that it is hard to believe that any reputable cable manufacturer would turn out such a cable.

There is a point of minor interest I should like to raise with regard to figure 12. The conductor of this cable consists of part normal-size wires, together with a number of smaller sized wires in groups of three. Was there any particular reason for this method of construction?

Martin Hochstadter (Brussels, Belgium): My interest in the development published in this paper has been great for two reasons:

Firstly, because this is real pioneer work opening a new field of insight into questions of outstanding practical importance in electrical cable engineering, a field which curiously enough, has been more or less entirely neglected hitherto. Not only do I see great merit in the very discovery of such a new field and its courageous and successful attack, but also do I believe this to be of a refreshing effect on the minds of our younger generation of cable engineers. Seeing every day nothing but work on details of problems which have already been principally dealt with by others, they might be led to the conclusion that no exploration field was left to them. This paper gives evidence of white patches on the map of our technical knowledge.

Secondly, the author's problem has been occupying me during the greater part of the last ten years. Research on pressure cable was carried out at first with internal pressure, namely, with cables of such construction that the pressure medium was acting in or near the conductor. However, the pressure effect on the dielectric was found to be of rather an imperfect and unreliable nature in all such cases. After much research and speculation into the causes of such unexpected behavior it was recognized that the propagation of the pressure through the dielectric, while being rather complete and instantaneous when external pressure compresses the dielectric, is poor and uncertain when the dielectric expands under the influence of internal pressure.

Pressure in such a semisolid body is propagated from layer to layer. In the case of internal pressure this propagation consists in the elastic stretching of each individual layer. Therefore, it can only take place there where layers touch each other and are under about the same mechanical stress neutrally, that is, before the application of pressure. It is, therefore, evident that a uniform propagation of internal pressure is contingent upon uniformity of the mechanical structure of the dielectric and that the internal pressure may be stopped totally or partly at any point in the dielectric where tightly wound papers are followed by loose ones.

While at the time of which I speak the relation between propagation of internal pressure and mechanical uniformity of the dielectric was made evident, no exact measurements of the latter could be taken and it was not possible to overcome the difficulties for using internal pressure. Therefore, external pressure has been used hitherto for the pressure cable. However, the author's methods for the demonstration and exact measuring of the mechanical uniformity of the dielectric may well lead to such an improvement of the manufacturing methods that a sufficient and controllable mechanical uniformity of the dielectric be obtained for the use of internal pressure in pressure cables.

This is one of the practical possibilities which the author's methods may open in a particular field of cable making besides others for the improvement of electric cables in general.

Hugo Sonnenfeld (nonmember; Bratislava, Czechoslovakia): The present paper completes the impression experts have obtained by its predecessors. The wafer method is certainly contributing to the possibility to have a reliable look into the working of the cable, especially the insulation and the lead sheath.

Even though there are only a few pictures published in the present paper they are sufficient for showing the way to improve cable design. Compound migration being, as is well known, a very important factor, it is evident that the first step for making cable service more reliable than it is now, consists in reducing filler space as far as possible. The general practice to use sector-shaped conductors cannot be considered as the best way. This appears to be quite clear if thorough consideration is given to the wafers shown in the present paper. Filler spaces are at the minimum in the case only that the *theoretically exact sector shape* is used, such as illustrated in figure 4 of the present paper. The photograph of this wafer, however, makes it evident that the insulation is rather a nonuniform one, and this particularly due to the shape of the conductor. Not only is the conductor, on two sides, flat so that its surface does not follow the natural bulge of the paper but the unequal electrical stress on the shoulders on one side and on the sector back on the other as well as on the flat parts on third side, is in no case able to fulfill requirements of high-voltage cables. For these various reasons the theoretical exact sector shape (see figure 4) is not advisable for high-voltage purposes. In the paper the expression "extreme sector" is used for such a shape of conductor, see page 148. We should not forget that this shape of sector is the only one which brings the filler spaces to their minimum.

If, however, the sector shape deviates from the theoretical exact "extreme sector" form, we come to designs such as is illustrated in figure 5. Here the gross irregularities, discovered in figure 4, are absent, the shoulders of the conductor being less sharp and the conductor more able to conform to the natural bulge in the paper. But all this is accompanied by the serious disadvantage of filler spaces evidently becoming larger. For this latter reason such cable does not represent the best possible design.

A round conductor offers little difficulty. It is to be expected that all disadvantages illustrated by figure 4 will not be present if the same machines and the same manufacturing method are applied but with a round or oval-shaped conductor. No doubt, the circular or oval shape is in any respect the best form of the conductor. If small fillers are used, resulting in a triangular shape of the lead sheath (so-called *S.O.* type cable) the reduction of the possibility of compound migration improves the properties of the cable and the cost of the cable containing circular (or oval) conductors is brought down to the cost of the cable containing sector-shaped conductors.

Thus the application of round (or oval) conductors together with the application of the triangular shape of the lead sheath makes available the following advantages of the cable:

The volume of oil compound causing expansion is reduced.

The radial resistance to oil flow is brought down to a minimum.

The thermal resistance is equally brought down to a minimum.

The facility to wrap paper with exact regularity upon the conductor is increased.

No pretwisting is necessary.

K. S. Wyatt, D. L. Smart, and J. M. Reynar: The authors are grateful for the favorable reception accorded the methods proposed for studying the mechanical uniformity of paper-insulated cable. It appears, however, that although the tools themselves have been accepted almost without qualification, the interpretations which were made in terms of design, manufacture, and service life have furnished many points of controversy. The primary purpose of the paper was to offer new test methods for obtaining data which might be of assistance in studying the relative merits of different types of construction and in determining the causes of insulation failure. Since the value of the wafer method depends, as in the case of X-ray photography, on correct interpretation, it appeared advisable to present tentative interpretations of cable wafers as samples of what to look for in the wafers and of how irregularities might be traced to original sources. A certain amount of theory was necessarily involved in these interpretations. Space limitations necessitated a rather cursory treatment of this phase of the paper with the result that many unintended inferences were drawn by readers. In addition, it was only to be expected that, in view of the relative newness and limited use of the method, the interpretations would be questioned as were those of X-ray photographs in the early days of their use. Furthermore, the necessary omission of a large number of illustrations representing reasonably good cable wafers undoubtedly caused an erroneous impression in some minds regarding our estimate of the quality of the average modern cable.

Several discussers point to the apparent futility of producing mechanically perfect insulation in view of the amount of relatively rough handling the cable undergoes during installation. The authors direct attention to the fact that the wafer method now enables us to evaluate the effects of such treatment. Time has permitted only meager investigation of this phase of the problem but, for what they may be worth, the results obtained do not indicate any serious damage to be sustained by a mechanically well-built cable when installed by modern methods.

If it appears, as stated by several discussers, that the paper overemphasized the effects of ionization and attached too much importance to the length and condition of the leakage paths, it is because the facts revealed by a careful study of scores of cable wafers lead, first, to a critical inspection of previously held theories of the mechanism of cable failure and, finally, to a tentative revision of these theories to better fit the observed conditions. Among these conditions were three which were frequently observed and which experimental evidence and theoretical considerations indicate have an important bearing on insulation breakdown. Two of these conditions involve butt-space distribution as it affects effective solid insulation thickness and minimum leakage path, and the third involves thick interlayer spaces caused by loosely wound insulation. An explanation of the part played by these factors in insulation failures would entail much theoretical discussion and would perhaps, be out of place here. The discussion by Professor Dawes, however, may serve to partially explain the phenomena responsible. The following briefly summarizes the conclusions of the authors as a result of their initial investigations:

(*a*) Ionization is held to be the chief cause of inherent insulation failure.

(*b*) The theory of D. M. Robinson that breakdown starts at the conductor and proceeds slowly through the insulation by a coring and tracking mechanism is accepted with reservations as to the importance of voids in the middle of the insulation wall.

(*c*) Conditions conducive to ionization are present in much cable as manufactured and may be aggravated due to service or to improper handling during installation. (Initial voids, even though they be filled with oil and thus do not cause high *initial* ionization, are considered to be conducive to ionization.)

(*d*) The development, during service, of conditions conducive to ionization may be minimized by proper design and manufacture.

(*e*) The inevitable presence of butt spaces at the conductor and other inherent weaknesses in the insulation of solid-type cable are not arguments against the elimination of other defects since many of the latter add to the basic inherent weaknesses to further decrease the over-all insulation efficiency.

(*f*) As the quality of the cable insulation is made more uniform due to precision methods of manufacture, the thickness of the insulation may be reduced because it is no longer necessary to provide a factor of safety to take care of avoidable but uncontrolled weaknesses.

It is seen that we do not agree in toto with Mr. Beaver's postulates (*b*) and (*c*).

The elimination of registrations and also of interlayer gaps is bound up with the taping machinery. We are in agreement with Mr. Beaver as to the advantages of certain types of "lapping machinery," but we must point out that they possess several apparently inherent disadvantages, among which is slowness of taping. If the paper is impregnated prior to taping, the trapping of gas between adjacent layers of insulation is an additional disadvantage. The design of taping machinery plays a most important part in the quality of cable insulation and the wafer method permits a visual study of the effects of the various design factors. For best results it is the belief of the authors that taping machines should have the following characteristics:

1. Direct drive throughout with as few gears as possible, since these introduce backlash.
2. Slow, smooth, but positive starting, without slippage, and brakes which stop the machine smoothly but reasonably quickly.
3. Direct synchronization between capstan and taping heads to eliminate the possibility of backlash or slippage.
4. A tape tension control in which centrifugal effects are absent and in which the tension of the tapes is independent of the amount of tape on the pad.

This is a subject deserving of much space. Suffice it to say here that hydraulic drive and synchronization appear to the authors to offer the best solution of the problem of precision taping at reasonable cost.

Mr. Del Mar and Doctor Wiseman infer that a uniform tape tension from conductor to sheath was recommended. Such an inference was not intended and may have been due to the fact that the torsion curve shown for uniform insulation was fairly level from conductor to sheath. The only relatively uniform cable which we had examined by means of the torsion test at the time the paper was written did not have the drooping characteristic from conductor to sheath which we believe to be desirable from the standpoint of ability to withstand bending without distortion. The same discussers also question the desirability of a high tape tension with a corresponding thin oil film between tapes. We believe, and support is given to this viewpoint by the discussions of Mr. Hochstadter and Mr. Jolin, that this film should be as thin as is consistent with good bending characteristics for a number of reasons. First, less oil is present and void formation is less likely to occur as a result of differential thermal expansion. Obviously tracking in service would be expected to be retarded or possibly eliminated. Second, the thinner the oil film, with other things equal, the less the comet's tail effect produced during cabling. Third, a very thin oil film which will permit successive paper layers to come into practically direct contact permits capillary effects to work to greatest advantage to distribute oil during impregnation, to prevent imigration and drainage during operation, and to return oil to the interior of the structure as the cable cools.

Several discussers have wrongly inferred that the study of cable wafers has led us to recommend a 50-50 overlay. The fact that with such an overlay the effective solid insulation thickness is only 50 per cent, coupled with the observation that due to the superposition of alternate butt-spaces the paper between has a tendency to tear when the cable is bent, would not permit such a recommendation. No attempt has been made by the authors to evaluate the relative importance of effective solid insulation thickness and minimum leakage path as factors in insulation failure for the purpose of selecting the best overlay. For this reason the report of the study of tape staggering made by Mr. Del Mar is particularly interesting. Accepting, for the sake of this discussion, his figure of 50 for the relative strengths of the radial and tangential dielectric paths, we do not believe that figure 1 of the discussion is a correct picture of the variation in effective insulation thickness with overlay. In the first place, it seems apparent that the values given in column 6 of table I should read as follows: 430, 387, 344, 301, 258, 215, 129, 86, 43, and 0. The figures in column 7 should be changed to correspond. Furthermore, if it be assumed, as seems reasonable, that failure may proceed, not only along *either* the radial path *or* the tangential path, but along a combination of *both* types of path, neither column 5 nor column 7 represents the shortest equivalent leakage path for many overlays. For example, with an overlay of $^{9}/_{32}$ inch or 39 per cent, the radial path through a tape to the butt space in the next layer would be less than $^{1}/_{50}$th the length of the tangential path to the same layer, and failure would occur by alternate ruptures of a tape and tracking to a point opposite the nearest butt space in the next layer. The effective insulation thickness would then consist of 110 mils of paper plus, 1,302 mils of leakage path which would total 136 mils equivalent insulation thickness. This is less than the figures in either column 5 or 7 for this overlay. Similar calculations for $^{8}/_{32}$-inch and $^{6}/_{32}$-inch overlays, when combined with the changes in column 7 mentioned previously, result in the modified curve shown in figure 2. This curve is markedly different from that shown in Mr. Del Mar's figure 1 and, incidentally, appears to fit the results of his voltage-time tests more closely, although we cannot agree with Mr. Del Mar's and Mr. Beaver's use of the results of voltage-time tests as an indication of the behavior of cable in service.

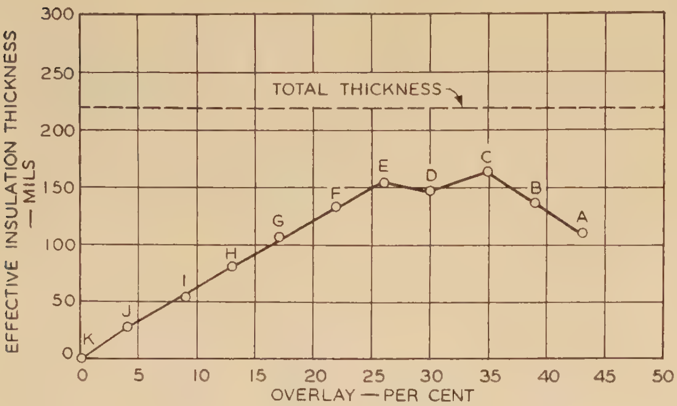


Figure 2. **The effect of overlay on the effective insulation thickness**

Mr. Jolin points out that difficulties are encountered in insulating sector-type cable and Mr. Sonnenfeld discusses the effect of the conductor shape on the ease with which a uniform insulation may be obtained, and on the filler-space volume. These are questions which the wafer method of examination should be of inestimable value in answering.

We agree with the discussers that much can and should be done to simplify the making of wafers. In his oral discussion, Mr. Meyerhoff described one method of simplifying the preparation of wafers from the styrenated cable sample. In this method, very thin wafers were cut with a band saw without finishing the faces on a lathe. The opacity of the sawn faces was eliminated by coating the wafer with a thin cable oil and mounting it between flat glass plates, care being taken not to wipe off all the surplus oil from the wafer. The development of a type of styrene or other material having a lower polymerization temperature and a shorter setting time would prove to be an important step. It is also suggested that the time of extraction might be shortened by permitting the styrene to trickle through the insulation continuously rather than to wash out the oil by the cyclic bath method described in the paper.

The apparatus originally used for making the penetrometer and torsion tests was admittedly crude. Since the paper was presented, however, the instruments have been considerably refined and combined into a single instrument which will be marketed by a well-known scientific instrument manufacturer. An article on the use of the compactness tester is being prepared, and it is expected that it will be published shortly in the technical literature.

In answer to Mr. Jolin, the authors are unable to give a reason for the design of the conductor shown in figure 12 of the paper. This cable was manufactured over eight years ago. It is believed that there was no intention of using the space between the strands as an oil duct and it is apparent that oil expansion would be more severe because of the large oil volume.

Mr. Dwight's question will have to be answered by others. So far as the authors know, such an application of the wafer method has not been made. The method has been used to advantage on trunk telephone cables in several countries. We believe it has a useful application in the study of many laminated dielectrics where uniformity of structure is of importance.

Our acknowledgment unintentionally omitted a word of appreciation for the support we received from engineers of other utilities. Possibly without this encouragement, this research could not have been carried to successful fruition.

Transactions

Papers and Discussions Comprising Pages 493–558 of the 1938 Volume

System Planning and Operation for Voltage Control

By T. J. BROSNAN
MEMBER AIEE

THE two criteria of the performance of any system for the delivery of electric energy are, first, its dependability as measured by continuity of service, and second, the quality of the service as measured primarily by the ability of the system to keep the deviations from normal voltage within acceptable limits. The purpose of this paper is to consider the influence of the second of these two factors, namely voltage regulation, on the design and operation of the system.

The permissible limits of voltage regulation vary for different types of load. It is generally regarded as good practice to keep the voltage at the service switches of residential and commercial customers in an urban area within three per cent above or below the normal level. For the same type of customers in rural areas, it is economically impractical to limit the deviations to less than five per cent above or below normal voltage. Industrial customers in general do not require such close regulation.

The following sections of this paper will review the influence of these limitations on the design and operation of the various parts of the system.

General System

In a typical modern distribution system the same subtransmission circuits serve different types of substations as well as transformer vaults in the low-voltage network system.[1] Provision is made for control of the voltage at the bus of the generating or terminal station but the difference in time characteristics of the various loads and the different electrical characteristics of the distribution systems make it essential to supplement this basic regulation with other methods of voltage control.

The generating-station bus voltage is regulated to meet the requirements of the load supplied through the low-voltage network system and provision is made for independent voltage control at the substations supplying residential, small commercial, and small industrial loads. Generally the large industrial loads do not require such close voltage regulation and it is unnecessary to add supplementary voltage control in the substations supplying such loads.

Substations

Automatic substation equipment has made it economically possible to use smaller substations which can be located relatively close together and near large concentrated loads.[2] The close spacing of substations results in short distribution feeders which in turn permit automatic regulation of the substation bus voltage rather than independent regulation of the voltage of each feeder.

In regulating the voltage of the substation bus, it is desirable to introduce a "rising characteristic" with increasing load in order to offset the increasing voltage drop in the distribution system beyond the substation. The "line drop compensator" which has been used for years for this purpose with individual feeder regulators can still be used with the equipment for bus regulation. The setting of "line drop compensators" even for individual feeder regulation involves a compromise between the customers closest electrically to the substation and those farthest removed electrically. With short feeders and bus regulation the problem is no more difficult. The "line drop compensators" are adjusted to give the best average regulation for all of the customers on one small substation instead of one long feeder. The one satisfactory method of keeping the "line drop compensators" properly adjusted in either case is by periodic checking of service voltages of customers close to and remote from the substation during the heavy load periods.

The actual line-to-neutral voltages on the busses of the small automatic substations in Buffalo range from 2,420 at periods of very light load to 2,500 at the time of heavy load. In terms of service voltage this is a range of 121 volts to 125 volts.

Distribution Feeders

There may be a few feeders where the voltage along the entire length of the feeder cannot be kept within the desired limits by means of regulation of the substation bus voltage. For such cases there are several types of feeder-voltage regulating equipment available for pole-top mounting. These can be inserted in any part of the feeder where they will be of greatest value in supplementing bus regulation.

It is evident from the foregoing that it is important to keep the voltage drop in all feeders supplied from one substation within a limited range. The total drop in voltage along a feeder is a function of its length, the magnitude and distribution of its load, its voltage rating, and the size and spacing of the conductors making up the feeder. The proper balance of these factors varies for different load areas. The following combination has been found satisfactory for the urban Buffalo area.

(*a*) All feeders are rated 4,100 volts, three phase, four wire. This system has the advantage of a voltage rating that is satisfactorily high for urban conditions and yet requires only 2,400-volt distribution transformers and incidental equipment. It has its main application in urban areas where all main portions of the feeders are three phase and all single-phase branches are short.

(*b*) The main "trunk" portion of every feeder is made up of 4/0 conductors. This

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[1] For all numbered references, see list at end of paper.

uniformity in conductor size facilitates rearrangement of feeders and simplifies the transferring of load from one feeder to another under emergency conditions.

(*c*) The load on each feeder is adjusted according to the length of the feeder so as to make the load multiplied by the distance to the load center as near a constant as possible for all the feeders out of one substation. Under the conditions prevailing in the Buffalo area, the maximum normal feeder loads vary from 800 kva to 1,200 kva.

For suburban and rural areas the 4,800-volt three-phase three-wire delta-connected feeders are more satisfactory than the 4,100-volt star-connected feeders because the single-phase branches form such a large part of rural feeders and it is very desirable to have the higher phase-to-phase voltage for these long branches.

Load balance between phases is very important on all three-phase feeders but particularly on three-phase four-wire star-connected feeders. This load balance should be maintained along the feeder as well as at the substations. The following system has been established for the control of this load balance in the Buffalo district.

A single-line diagram for each feeder indicates the phase to which each distribution transformer is connected and there is marked on this diagram the theoretical load balance at key points along the feeder. Whenever a new distribution transformer is added, the feeder diagram is used to decide the phase to which the new transformer will be connected. In this way all routine work tends to improve feeder balance. The theoretical over-all load balance of a feeder as taken from the diagram is checked periodically by the readings of the maximum-demand meters on each phase of each feeder at the substation.

Transformers, Secondaries, and Services

Any condition in a primary feeder resulting in poor voltage is serious because of the number of customers involved. However, as a result of the care that is taken in the design and operation of distribution feeders in a modern system, they are seldom the cause of poor voltage. The portion of the system that provides the real problem in voltage control is that made up of the distribution transformers, secondaries, and services because the voltage drops in these parts of the system are generally greater than in the short primary feeders in a modern distribution system.

There are so many distribution transformers, secondaries, and services in a distribution system that it is apparent each of these units cannot be given continuous individual attention. Yet, since any one unit when improperly designed, applied, or maintained may be the cause of poor voltage, it is evident that a careful set of standard designs and system of routine attention must be established to insure proper voltage control.

The importance of transformers, secondaries, and services in the voltage problem is further emphasized by a consideration of voltage complaints in the Buffalo district during 1937. Table I shows the number of cases of unsatisfactory voltage caused by each part of the distribution system.

Table I. Number of Justifiable Complaints by Cause During 1937

Portion of System Responsible for Poor Voltage	Number of Complaints	Per Cent of Total
Primary feeders	10	12.3
Transformers and secondaries	27	33.4
Services and customer wiring	30	37.0
Utilization equipment (oil burners, blower motors, flashing signs, etc.)	14	17.3
Total	81	100

The first important step to be taken in guarding against voltage troubles in the secondary portion of the distribution system is to prepare standard transformer-secondary designs for all conditions usually encountered in the field. Such standards must be based not only on proper voltage control but also on considerations of economy, ease of change when necessitated by load growth, and similar factors.

Such a set of standards prepared for the Buffalo district calls for number 2 wire for about 90 per cent of the secondaries. This means that growth of load in the great majority of cases can be accommodated by changing the size or spacing of transformers with no change of secondary wire. These standards are all based on keeping the voltage drop in the secondary within 1.5 per cent with full load on the transformer.

It is equally important to prepare standards for new service entrances to be installed by customers and corresponding service drops to be installed by the power company. This should include guides for the replacement of existing services when necessitated by load increases.

Much could be said about various methods for keeping continuous records for load so as to know when to change transformers. It is mentioned here because whatever system is adopted for field checking transformer loads should also check load balance on the three wire secondaries which is a very important factor in proper voltage control.

Utilization Equipment

Two characteristics of the new load being added to distribution systems today are disturbing to those engineers responsible for proper regulation of service voltages. The first is the low-power-factor characteristic of a large portion of the load that is being added. The second is the tendency of many of the new utilization devices to introduce sudden load changes which, if of sufficient magnitude and of frequent enough occurrence, may result in objectionable flicker. These statements refer particularly to automatic house-heating equipment, air-conditioning equipment, refrigerators, small arc welders, and similar types of apparatus.

It is becoming increasingly important, as more of this equipment is being added to the systems, that the electrical manufacturers, electrical contractors, and electric power companies co-operate to insure the proper operation of this equipment without interference with other loads and at the lowest over-all cost to the industry.

One of the most important steps in such a co-operative program should be the introduction by all electric power companies of reasonable motor-starting-current limitations based on the true capacity of the distribution systems to accommodate such starting currents without serious voltage disturbance in place of limitations based on the size of the motor.[3]

Conclusion

While voltage regulation is the most important criterion of the quality of the service rendered by an electric delivery system, very few customers purchasing electric service have any means for measuring this quality other than by comparison of present with past performance of their utilization equipment. If their lamps seem to burn out at a faster rate than normal, they conclude that the voltage is too high. If the lamps burn with less brilliance than normal or the elements of the range heat at less than normal rate, they conclude that the voltage is too low. This introduces an important psychological factor. For example, an analysis of the voltage com-

Regenerative Tension Control for Paper Winders

By H. W. ROGERS
ASSOCIATE AIEE

THE WINDER is one of the more important machines in the paper industry. In general, every paper machine has a winder intimately associated with it and there are many others used in the finishing room.

It is not strictly a part of the paper machine, but is very closely allied to it since its function is to take the reel of paper from the paper machine, trim it, slit it to the proper width, and rewind it into smooth, even density rolls of the proper size for shipment; and since it starts and stops frequently to change rolls or make splices, it must operate at speeds greatly in excess of the paper-machine speed to keep up with production.

The Winder

It consists essentially of an unwinding stand on which the roll of paper to be rewound is mounted, several free-running steel rolls over which the paper passes, a slitter, a spreader bar, and a pair of winding drums on which the roll of rewound paper rides. See figure 1.

Power is applied to the winding drums, which in many instances have been either geared or belted together in such a manner that the leading roll travels slightly faster than the trailing roll. The object of this method of drive is to wind a uniformly tight roll of proper density.

More recently there has been a definite trend toward using a separate motor on each winding roll, with provision for adjusting the relative load on each motor, thus insuring the proper winding conditions at all times for any kind of paper.

To operate successfully, and wind smooth even density rolls, there must be tension in the sheet of paper. The object of the tension and the spreader bar is two-fold: first, to remove all wrinkles from the sheet, and second, to wind a tight roll of even density. Heretofore, tension has been obtained by means of a manually adjusted band brake on the unwinding roll stand, and while it is possible to automatically control the brake, it is difficult to hold constant tension with such a device since the unwinding roll may vary in diameter as much as five to one during the operation. In a large majority of cases, this band brake is manually operated and in such instances it is impossible to hold anything that approaches constant tension, since the operator has no real indication of the tension in the sheet.

Devices of this type are, of course, in operation, and will continue on the smaller machines, possibly on the larger machines winding light-weight papers, but the trend toward wider, high-speed machines and heavier papers has so increased the power involved that the dissipation of heat in a mechanical brake is a real problem and the maintenance may become a major item of expense.

Characteristics of Paper

The situation may be more readily appreciated if we go back to fundamentals and discover some of the characteristics of paper. Figure 2 shows the relation between per cent stretch and pounds pull per inch width in per cent of ream weight, (500 sheets, 24 by 36 inches) for uncalendered kraft paper, and while this curve may vary for other grades of paper,

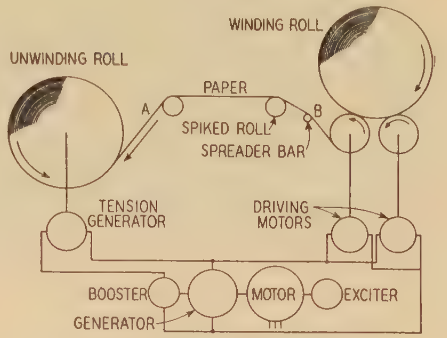

Figure 1. Diagram of a paper winder

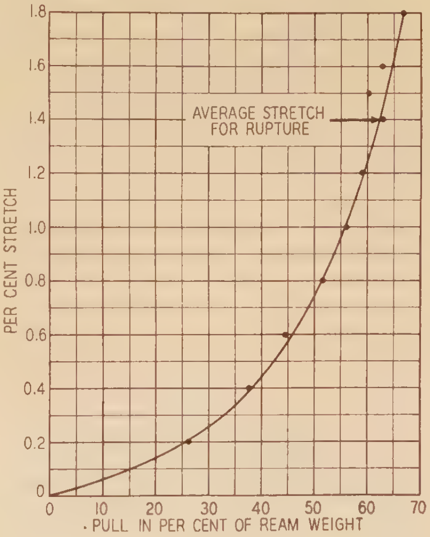

Figure 2. Characteristic stretch curve for uncalendered kraft paper

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plaints received from customers in the Buffalo district during 1937 shows that only 3.5 per cent of the high voltage complaints were justified whereas 80 per cent of the low voltage and flickering voltage complaints were justified.

There has been a very interesting example in the Buffalo district of the effect that major system changes can have on the psychological factor. During the years 1930 and 1931, the supply to all of the residential load and most of the commercial load in the Buffalo district was changed from 25 cycles to 60 cycles. A complete new distribution system was installed and the normal service voltage was raised from 115 to 120 volts as a part of the same operation. The number of voltage complaints rose steadily during this major change reaching a peak during the year 1932 at about double the number recorded in any year prior to the start of the change. There has been an appreciable decrease each year since 1932 so that the total number of complaints during 1937 was only one-quarter of the 1932 peak. The interesting feature is that during this entire period there has been very little change in the annual number of complaints found to be justified.

References

1. FUNDAMENTALS OF DESIGN OF ELECTRIC ENERGY DELIVERY SYSTEMS, **J. Allen Johnson** and **R. T. Henry**. ELECTRICAL ENGINEERING, December 1933.

2. 100,000 KW DISTRIBUTION SYSTEM AS A SINGLE PROJECT, **R. T. Henry**. *Electrical World*, July 25, 1931.

3. MOTOR STARTING CURRENT STEPS BASED ON CONNECTED LOAD, **T. J. Brosnan**. *Electrical World*, April 28, 1934.

it is undoubtedly characteristic of all grades of paper. It is based on some 18 samples varying in weight from 25 pounds to 70 pounds. A few samples ruptured at 1.8 per cent stretch, none ruptured at less than 1.0 per cent stretch and the average rupture was at 1.4 per cent stretch.

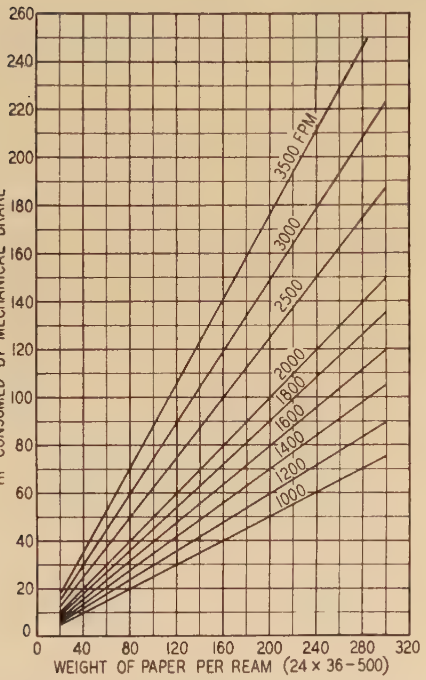


Figure 3. Power consumed by a mechanical brake on a 200-inch winder

Sheet Tension

Experience seems to indicate that a tension of approximately 4.0 per cent of the ream weight per inch width of sheet is sufficient to wind properly a roll of paper. This corresponds to a stretch of approximately 0.02 per cent, well within the rupture point, and up to the present time seems to have met all operating requirements.

Losses Due to Tension

This tension, expressed in pounds pull per inch width of sheet may not appear imposing, but when combined with a wide sheet and high speed, it presents a materially different picture. Figure 3 shows the power consumed by a mechanical brake in maintaining proper sheet tension on a 200-inch-width winder when operating at various speeds with different weights of paper. It also approximates the amount of power returned to the line on a regenerative electric tension-control system.

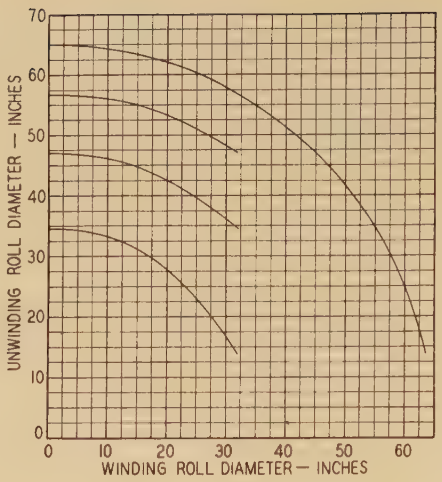


Figure 4. Corresponding diameters of winding and unwinding rolls for paper winders

Regenerative Tension Control

The idea of regenerative tension control is not new, but the enormous expansion of the paper industry, the building of many new kraft mills in the South and the more general use of this kind of paper for containers and innumerable other uses has fostered many changes and developments in this type of equipment to meet the more exacting conditions of operation.

Operating Requirements

The operation of a winder requires a smooth, easy start, continuous slow speed while paper is being threaded through the machine and for making splices, smooth acceleration from standstill to maximum speed, rapid smooth deceleration, and at times, a quick stop.

With the mechanical tension control the operator must rotate the unwinding roll by hand during the threading operation. This is not objectionable on the smaller machines, but the trend towar wider machines and much larger dian eter paper rolls places a burden on th operator as some of these rolls weig six or seven tons. Provision shou therefore be made to turn these rol over by power during the threadi operation.

Furthermore, these heavy rolls paper have an enormous amount energy when the winder is running

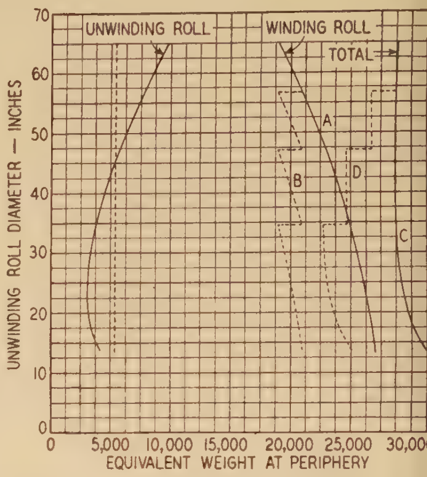


Figure 5. WR^2 of winder reduced to equiv lent weight at the periphery

full speed, and provision for quick sto ping is essential.

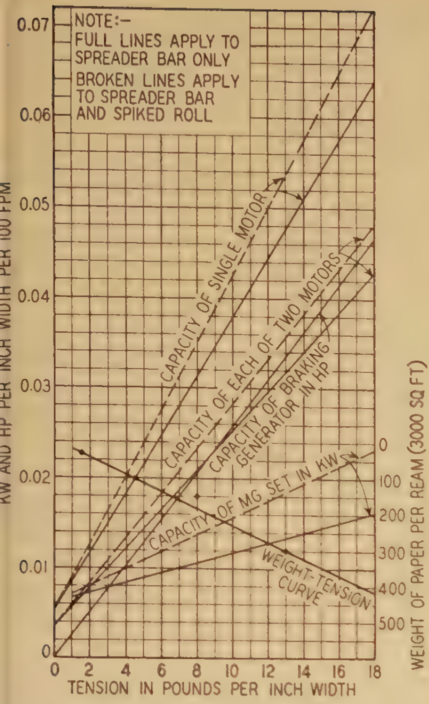
The Modern Winder Drive

One of the modern high-speed wind drives is of the Ward Leonard type wi two compound-wound d-c driving m tors, a d-c tension generator, a mot generator with booster unit and excite the necessary control and a current reg lator. The control of the winder spee

Table I. Acceleration Data for a 228-Inch 3,000-Foot-Per-Minute Winder

	Total Machine			Unwinding Roll		
Diameter of Unwinding Roll (Inches)	Equivalent Weight (Pounds)*	Force to Accelerate	Horsepower Torque to Accelerate One Roll	Equivalent Weight (Pounds)	Force to Accelerate	Horsepow Torque t Accelerat
65	28,875	2,245	204	9,750	758	69
60	28,800	2,240	203.5	8,500	641	58.2
55	28,750	2,235	203	7,375	572	52
50	28,750	2,235	203	6,250	486	44.2
45	28,750	2,235	203	5,300	412	37.5
40	28,750	2,235	203	4,500	350	31.8
35	28,750	2,235	203	3,800	295	26.8
30	28,875	2,245	204	3,375	262	23.8
25	29,250	2,270	206.5	3,125	243	22.1
20	29,750	2,310	210	3,125	243	22.1
13.875	31,250	2,430	221	4,125	321	29.1

* Winding one large roll of paper from one 65-inch roll.



igure 6. Power curves for selecting equipment capacity

s entirely by generator-field adjustment, and there is means of adjusting the load listribution between the two driving notors to insure a tightly wound roll vith any grade of paper.

The Tension Generator

The braking generator is very similar o the adjustable-speed d-c motor with a speed range by field control of four or ive to one depending on the maximum and minimum diameter of the unwinding roll. The four-to-one range is, however, less expensive and should be adhered to preferably. This can be accomplished very readily by increasing the core diameter of the unwinding roll a few inches, as it does not affect the maximum diameter materially, nor the amount of paper in the roll.

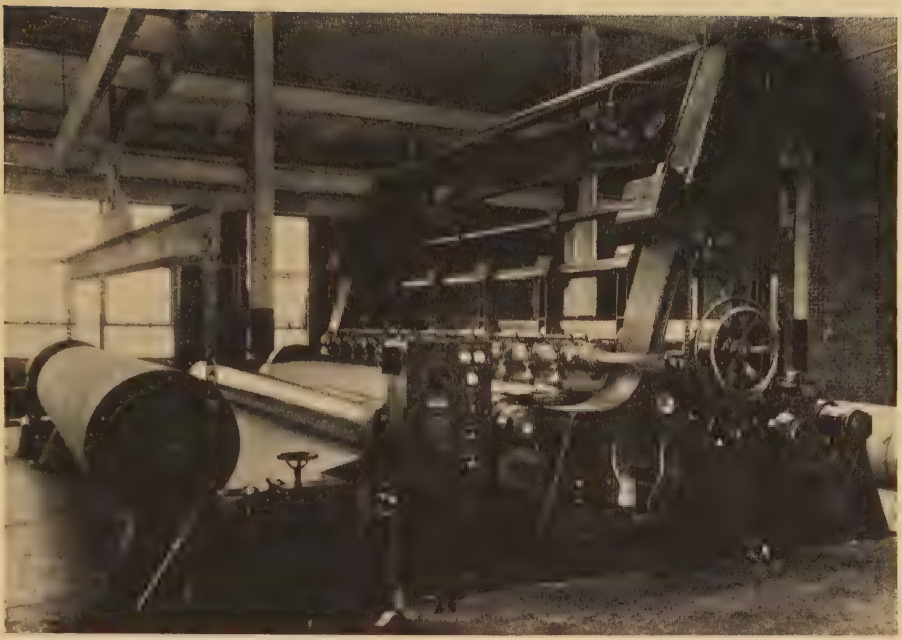


Figure 7. 234-inch, two-drum winder driven by an adjustable generator voltage winder drive with regenerative braking tension control. Winding speed 3,000 feet per minute

The Booster

The booster supplies the *IR* drop in the braking generator circuit and makes sheet tension immediately available when the winder is started up. Constant tension means constant horsepower or constant current for any given speed, but since with constant tension the horsepower varies directly with the speed, it follows that if constant current is held in the braking generator, the tension will be constant regardless of the winder speed or the diameter of the unwinding roll.

Table II. Power Data for Winders

*Power Data—With Spreader Bar Only

Tension at "A"**	Tension at "B"**	Friction Load	Tension Load	Total Load	Horsepower Returned	Main Generator Capacity	Tension Generator Capacity
0	0	0.00520	0.00000	0.00520	0.00000	0.00430	0.00000
2	2.163	0.00570	0.00606	0.01176	0.00575	0.00570	0.00517
4	4.326	0.00619	0.01210	0.01830	0.01150	0.00660	0.01035
6	6.489	0 00668	0.01820	0.02488	0.01730	0.00770	0.01550
8	8.652	0.00718	0.02420	0.03138	0.02300	0.00880	0.02070
10	10.815	0.00767	0.03030	0.03800	0.02880	0.00992	0.02600
12	12.978	0.00816	0.03640	0.04456	0.03460	0.01120	0.03120
14	15.141	0.00866	0.04240	0.05106	0.04030	0.01220	0.03630

*Power Data—With Spiked Roll and Spreader Bar

Tension at "A"**	Tension at "B"**	Friction Load	Tension Load	Total Load	Horsepower Returned	Main Generator Capacity	Tension Generator Capacity
0	0	0.00520	0.00000	0.00520	0.00000	0.00430	0.00000
2	2.489	0.00661	0.00606	0.01267	0.00575	0.00620	0.00517
4	4.979	0.00802	0.01210	0.02012	0.01150	0.00807	0.01035
6	7.469	0.00943	0.01820	0.02763	0.01730	0.01000	0.01550
8	9.958	0.01084	0.02420	0.03504	0.02300	0.01190	0.02070
10	12.611	0.01224	0.03030	0.04274	0.02880	0.01395	0.02600
12	14.938	0.01366	0.03640	0.05006	0.03460	0.01560	0.03120
14	17.429	0.01506	0.04240	0.05746	0.04030	0.01750	0.03630

* Power data is horsepower per inch width per 100 feet per minute except main generator which is kw.
** Tension is in pounds per inch width.

The Regulator

It is the function of the regulator to hold this current constant at whatever value it is set, depending upon the weight of paper being wound. Provision is made, however, for operating the braking generator as a motor during the threading operation, thus relieving the operator of considerable heavy labor.

Acceleration and Deceleration

Mention has already been made of the heavy inertia involved in large rolls of paper and since the sheet must bring the unwinding roll up to speed and involves considerable tension or pull, the regulator automatically eases off the current held by the braking generator to avoid breaking the sheet and when the winder is up to speed, it again holds the correct current. During the slowing down operation, the reverse is true; the regulator automatically holds a higher current to keep the sheet tight and prevent it from wrinkling.

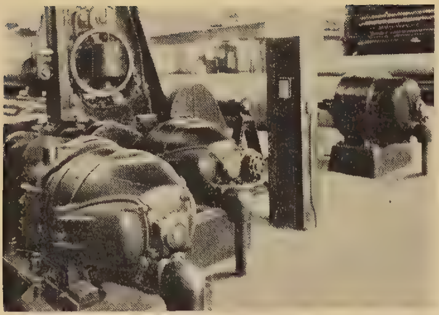


Figure 8. Adjustable generator voltage winder drive with regenerative braking tension control. Two 75-horsepower 1,750-rpm 230-volt driving motors. 50–60-horsepower 250–1,000-rpm 230-volt braking generator

As an illustration we may consider a modern winder of 228-inch width designed to operate at 3,000 feet per minute on kraft papers up to 150 pounds per ream.

The equipment consists of two 125-horsepower motors on the winding drums, one 125-horsepower 185/945-rpm braking generator, and a 60-kw motor generator set with the necessary booster, constant-current regulator, and control.

The winding drums are 20 inches in diameter, the rider roll and guide rolls are $13^7/_8$ inches in diameter, and the unwinding roll is 65 inches in diameter, wound on a $13^7/_8$-inch spool.

At any given operating speed, the speed of the braking generator must vary over a range of 4.7 to 1 and as the unwinding roll decreases in size the winding roll increases as shown in figure 4 with a consequent decrease in WR^2 of the unwinding roll and an increase in WR^2 of the winding roll. In many instances the operation is such that 30- or 32-inch finished rolls are the maximum size and four of these may be wound from a 65-inch roll of paper. The operation is, therefore, intermittent with frequent starting and stopping, and, in addition to the friction and tension load the motors must accelerate this heavy inertia from standstill to top speed in about 20 seconds.

The unwinding roll, instead of being driven, is held back by the braking generator to maintain proper tension in the sheet. During accelerating this tension is composed of two elements, the pull caused by the braking generator and the pull required to overcome the inertia of the roll. Therefore, to maintain a constant tension during acceleration, the tension caused by the braking generator must be reduced by an amount equal to the pull required to overcome the inertia.

To simplify the problem involved we may consider all of these heavy inertias as so much weight concentrated at the periphery of the roll of paper as indicated in figure 5 and calculate the power required to accelerate this weight in the required time.

Curve *A* and *C* figure 5 represents a single large winding roll while curves *B* and *D* represent four 32-inch-diameter rolls wound from one 65-inch roll of paper.

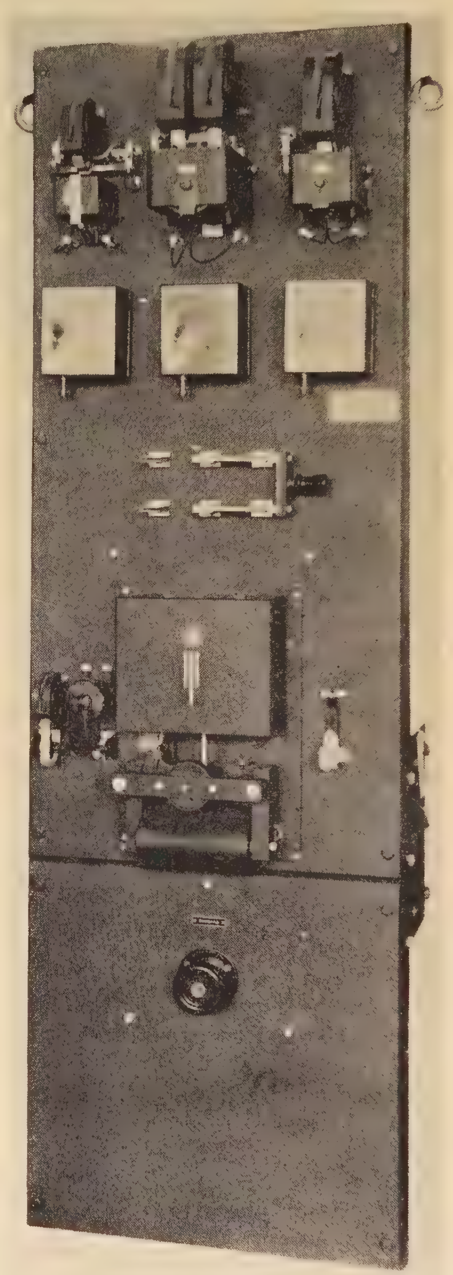


Figure 9. Main control panel for adjustable generator voltage winder drive

The tabulated data in table I show the equivalent weight of the complete winder together with the force and horsepower torque required to accelerate it in 20 seconds for various diameters of th unwinding roll. It also shows the equiva lent weight of the unwinding roll tc gether with the force and horsepowe torque required to accelerate it.

The average horsepower torque required to accelerate the complete winde is 205.7 while the average horsepowe torque required to accelerate the unwinc ing roll is 38; therefore, the tension hel by the braking generator should be decreased by a corresponding amount t maintain a constant sheet tension durin this operation. This is automaticall taken care of by the regulator throug the system of wiring connections.

When operating at top speed (3,00 feet per minute) the input to the drivin motors resulting from friction and shee tension is 212 horsepower while the powe returned to the line from the brakin generator is 137 horsepower leaving 7 horsepower to be supplied by the moto generator set. During acceleration th input to the motors (in terms of maximur speed) is 435 horsepower but because c the easing off in tension held by the braking generator, only 101 horsepower is returned to the line, leaving the moto generator set to supply 334 horsepower o 250 kw during this short period of time

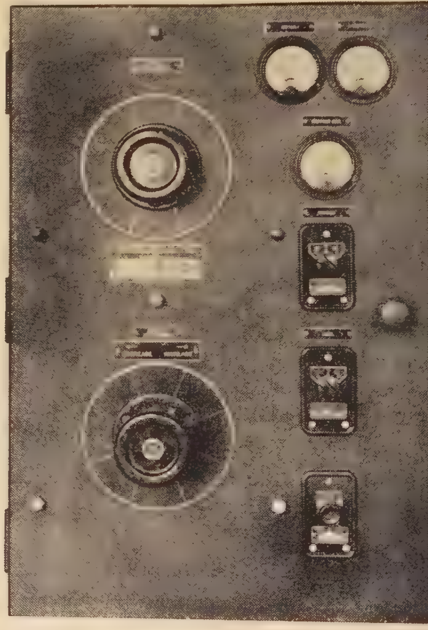


Figure 10. Auxiliary control panel for adjustable generator voltage winder drive

Dynamic Braking

Quick stopping is very importan especially on high-speed winders, an provision is made for electrical brakin on both the winder motors and unwinding roll. This feature has a considerable bearing on the selection of motor capacities where light-weight papers are involved because the inertia of the winder and the roll of paper are likely to have a greater bearing on the motor capacity than the sheet tension under these conditions.

Power Requirements

The power required to drive a winder is made up of friction load and sheet tension and while there is some slight variation in the friction load of different winders, it is permissible to assume an average friction load and calculate the power requirements on the basis of sheet tension, assuming that the spreader bar or spiked roll or both are used in the operation. Such power data have been calculated and are herewith submitted in table II and figure 6.

An attempt has also been made to indicate the approximate tension required for sheets of various weights, based on recent experience and tests on winders now in operation. This is indicated in the curve, figure 6, and while there are scant data on this subject, and some difference of opinion, it will serve as a guide to the trade in selecting the sheet tension. The capacity of the equipment, however, is definitely determined by the sheet tension and equipments for this service should be so specified.

Conclusion

The big advantage in this type of drive is in maintaining constant sheet tension at any desired value and correctly winding rolls of uniform density. The load distribution between the motors and the sheet tension is indicated at all times and fast smooth acceleration and deceleration are available.

Regenerated power, while not of primary importance, does nevertheless make available power which otherwise must be dissipated as heat, and permits of using much smaller motor generator sets than would otherwise be possible. For example, a 228-inch winder operating at 3,000 feet per minute on a 300-pound kraft sheet would require two 200-horsepower driving motors, a 100-kw motor generator set and a 225-horsepower braking generator, which, on the basis of 50 per cent operating time would save approximately 810,000 horsepower-hours per year; power which might be used to good advantage elsewhere in a mill.

Comparison of Methods of Stopping Squirrel-Cage Induction Motors

By W. I. BENDZ

APPLICATION engineers frequently encounter the problem of choosing between the several available methods employed to stop a squirrel-cage induction motor quickly. To the best of the writer's knowledge, little has been done to present data in such a way as to make it useful to draw direct comparisons between these schemes, discuss the advantages of each, and aid in the choice of the method best suited to a particular application. Such is the purpose of this paper.

The schemes most commonly encountered in industrial equipment are: (1) Braking applied by a magnetically released, spring-set friction brake either of the shoe or disk type, or (2) Plugging, using a reversing magnetic controller usually in combination with a "plugging" or "zero-speed" switch driven from the motor shaft, (3) A scheme which is rapidly gaining favor for industrial application is the application of direct current to one or more of the motor stator phases and thereby stop the motor by what has been commonly referred to as "dynamic braking." (4) A fourth scheme discussed herewith is dynamic braking using a capacitor and resistor in which case the motor functions as an induction generator. Occasionally, an application warrants combining two braking schemes to obtain a desired function of a drive. Some suggestions in regard to this are also discussed.

Magnetically Operated Friction Brake

Probably the oldest and certainly the most common method of stopping ac-motors is by means of a spring-set magnetically released friction brake. The coil of the brake magnet is usually connected directly across two of the motor terminals so that the brake is energized (released) whenever power is applied to the motor and the brake coil de-energized (brake set) when power is disconnected from the motor. Earlier construction was such that the brake frame was separate from the motor and the two units had to be properly aligned. Co-ordinated designs now usually include the brake frame with the rear motor bracket and mount the brake wheel directly on a rear extension of the motor shaft. This design has been used for many years although a recent modification has been the introduction of disk-type brakes rather than shoe brakes. The disk brakes are neat in appearance and completely enclose all rotating parts. Since there is no difference in the function of either type of brake, the comments which follow apply equally well in both cases.

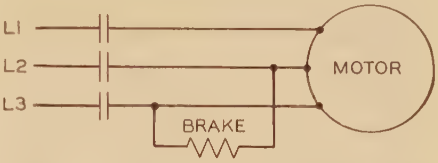


Figure 1A. Brake coil connected across motor leads

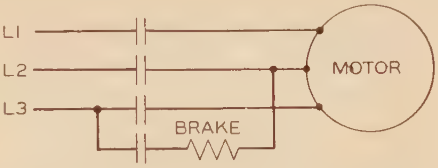


Figure 1B. Brake coil connected with separate circuit

The application of "thrustor" brakes has been omitted from this paper for the reason that the writer is herein mostly

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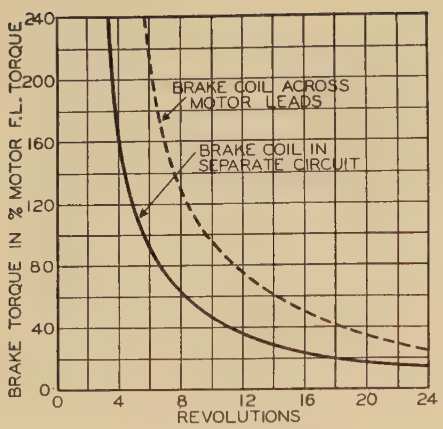


Figure 2. Comparison of brake-coil connections

concerned with motor ratings to which "thrustor" brakes are not usually adapted.

In all of the data which is presented, references to time or to the number of revolutions to stop a motor also includes the operating time of the magnetic contactor used for the motor control. This fact should be remembered when examining the shape of curves plotted against time or distance to stop.

The usual method of connecting a brake of this type is to wire the magnet coil directly across two of the motor leads, as illustrated in figure 1*A*.

The motor control disconnects the motor circuit and de-energizes the brake coil as well. This method of connecting the brake is simple and inexpensive since the brake is always beside the motor and the conduit wiring reduced to a minimum.

If the motor control switch is provided with an additional pole the connection shown in figure 1*B* can be used resulting in a considerable reduction in braking time. Any circuit which isolates one side of the brake coil from the motor can be used equally as well. The purpose of this connection is to completely de-energize the brake magnet at the same instant as the motor is disconnected from the line in order to bring about immediate application of the braking force.

The results of a test to show a comparison between these two connections, taken on the same motor and brake are plotted in figure 2. The dotted curve is the result of connecting the brake coil directly across the motor terminals as in figure 1*A* while the solid curve is the plot of performance when employing the separate brake coil connection shown in figure 1*B*. It is apparent that the difference in revolutions traversed during deceleration for the two schemes is greater at the lower value of braking torque. The explanation rests in the fact that the reduction in braking torque was obtained by weakening the spring of the brake. As the spring was made weaker the voltage appearing across the brake coil as a result of it being connected across the motor terminals caused increasing delay in the application of the brake, when this method of control was used.

The results shown in figure 2 were obtained on a three-horsepower six-pole frame *W*-254 motor equipped with a standard solenoid brake. The same tests were made on four- and eight-pole motors, both two and five horsepower. Similar results were obtained and in general it can be said that the difference between the two schemes is less for eight-pole motors and greater for four-pole motors. This is as would be expected since the higher speed motors will turn a larger number of revolutions for a given unit of time delay for the application of the brake.

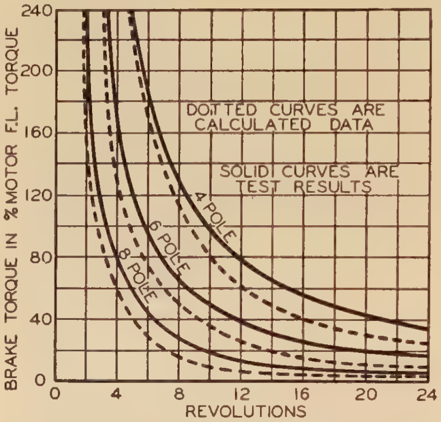


Figure 3. Comparison of calculated and test performance

The result of these tests brings about the conclusion that whenever maximum braking effect is required it is worth while to open the brake-coil circuit by means of a separate contact.

Figure 3 shows a plot of braking torque against revolutions to bring the motor to a stop for four-, six-, and eight-pole three-horsepower motors with the brake coil opened by a separate contact as in figure 1*B*. These curves may be considered as typical for motors of any horsepower rating but individual cases will depart from the performance illustrated due to variation in the ratio of torque to WR^2 for different motors. For this reason it seemed advisable to compare actual performance with theoretical calculated values from which one may consider the expected performance of any similar motor and brake.

The results of calculated performance for the motors tested in figure 3 are shown by the dotted curves. These were calculated from the braking torque, motor WR^2, and adding a factor of one-tenth second for the control and brake to operate. Tests showed that the average control and brake operated in about six cycles when the brake was adjusted for its maximum rating. A somewhat longer time was required when the brake spring (and torque) was decreased but this variation was neglected for the purpose of simplifying the discussion.

The importance of the curves plotted in figure 3 is that the performance as calculated from braking torque, motor WR^2, and control operating time checks reasonably well with actual operating conditions. Furthermore, it can be concluded that there is little to be gained by applying a brake rated much more than 100 per cent of the motor full-load torque and certainly no reason to exceed 200 per cent torque. This statement is true only when the WR^2 of the connected load is small compared with the motor. Choice of the proper brake must take this into account.

Figure 4 shows a plot of braking torque against time to stop the motor for six- and eight-pole three-horsepower motors. While other ratings were tested the results were not included in the figure because of the confusion of curves. As was brought out during the discussion of figure 3, calculated performance is reasonably accurate from which other ratings could be added to figure 4.

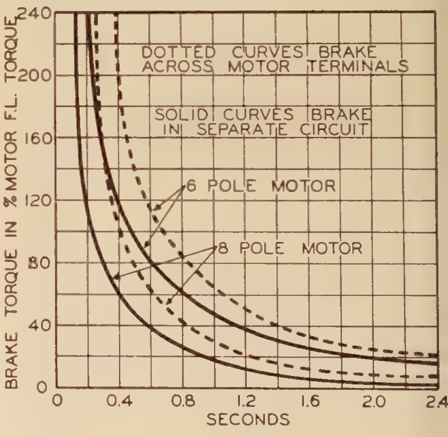


Figure 4. Comparison of brake-coil connections

The solid curves of figure 4 are the results obtained when using the separate brake coil connection shown in figure 1*B* and the dotted curves correspond to the connection of figure 1*A*.

To summarize the application of agnetic brakes the following conclusions ay be drawn:

. When the maximum braking effect is equired it is worth while to select the con- rol to provide the separate brake-coil cir- uit as shown in figure 1*B*.

. Except in cases where the WR^2 of the onnected load is a considerable portion of or reater than the motor inertia, there is not uch gained by selecting a brake rated ore than 100 per cent of the motor full oad torque; no practical gain by exceeding 00 per cent torque.

. Theoretical performance calculated by he following formulas are sufficiently close or most practical applications:

$$\text{ime to stop} = \frac{WR^2 \times \text{rpm}}{308 \times \text{brake torque}} + 0.1$$

evolutions to stop =

$$\frac{WR^2 \times (\text{rpm})^2}{3.70 \times \text{brake torque}} \times 10^{-4}$$

here

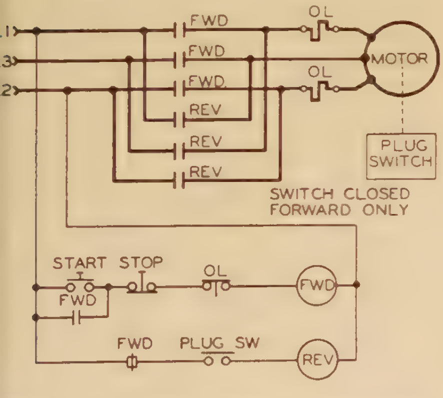
ime is in seconds

rake torque is in pound-feet

R^2 is in pound-feet^2

lugging Squirrel Cage-Motors

Plugging control to stop squirrel-cage otors is becoming more widely used for any kinds of industial applications. The reasons for this are (1) the increased apacity of feeder systems, thereby more niversally eliminating the objection to he relatively high line current required or effective stopping, (2) the improve- ent in motor design to electrically and echanically withstand the stress during lugging, and (3) the availability of roper and reliable control apparatus for lugging service.



igure 5. Schematic diagram of full-voltage plugging control

The majority of plugging applications re those for which the motor is connected cross the power lines at full voltage by eans of a pair of reversing contactors. A typical magnetic push-button control for this purpose is shown in figure 5.

A plugging switch, frequently referred to as a zero-speed switch, is driven from the motor shaft or from machine shafting coupled to the motor. This type of switch is designed so that its contacts close only due to rotation in one direction and are therefore open at zero speed or reverse rotation. Inspection of the diagram shows how the normally closed interlock of the "forward" contactor prevents the "reverse" contactor from being energized while the motor is running forward. As soon as the "stop" push button is depressed the circuit to the "reverse" contactor is completed through the "forward" interlock and plugging switch. The motor is then plugged to rest and at zero speed or upon slight reversal the plugging switch opens its contacts and de-energizes the "reverse" contactor.

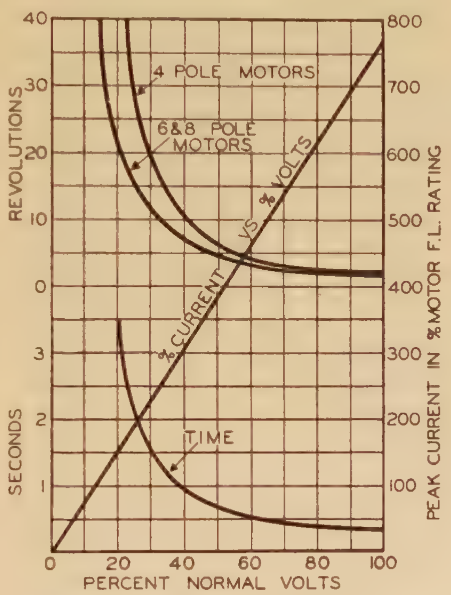


Figure 6. Performance by reduced-voltage plugging

Control is also available for reversing service in which case the plugging switch has two sets of contacts, one of which is closed by the forward rotation and the other by backward rotation. The motor is plugged to rest when the "stop" push button is depressed, no matter in which direction the motor may be running.

Figure 6 shows a plot of time and also the number of revolutions to stop against motor voltage in per cent of the normal rating. The voltage referred to is the value existing across the motor terminals at the instant of first starting to plug. The reduction in voltage below normal is obtained by connecting equal resistors in the three motor lines. Therefore, the abscissa and the right-hand ordinate are values occurring at the same instant.

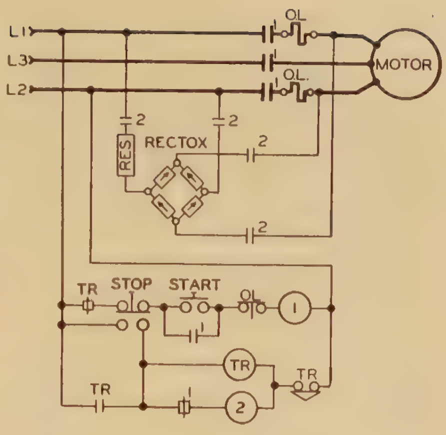


Figure 7. Schematic diagram of d-c braking control using copper-oxide rectifier

This figure also includes a plot of peak current required to plug a motor at any given per cent of normal voltage. By use of these curves the peak line current required to produce a desired rate of deceleration can be determined.

The data from which figure 6 was prepared were obtained by testing a number of motors between one-quarter and ten horsepower, four-, six- and eight- pole. Although the curves of this figure represent average values for this wide range of ratings it is important to note that individual cases did not depart from the average curve more than 10 per cent in regard to revolutions or time plotted against per cent voltage. However, there was a somewhat wider variation when considering the peak current drawn at 100 per cent normal voltage and this factor should not be overlooked when applying this data.

It is important to note that the results shown refer to a constant line voltage. If the line potential is decreased during the plugging interval the performance is changed radically. As an example, a test was made on one motor, holding the line voltage constant and adjusting series resistors to limit the plugging current to 400 per cent which resulted in 5.0 revolutions to stop the motor. The same motor was connected across a generator and feeder system of such poor regulation that the plugging current was also 400 per cent but without any series resistors. In the latter case the motor required 8.0 revolutions to stop or an increase of 60 per cent.

The amount of resistance to connect in series with the motor to limit the plugging current to any desired value can readily be calculated from the motor locked-rotor current and power factor.

Once the approximate motor reactance has been calculated the resistance can also be obtained. The required impedance is figured, knowing the maximum permissible line current and from this the total circuit resistance is obtained. Subtracting the motor resistance leaves the value to be added to each line.

Dynamic Braking by Applying Direct Current

Dynamic braking of a squirrel-cage motor by disconnecting the a-c power and applying direct current to one or more stator phases is not a new scheme but has not been widely used to date. Perhaps lack of sufficient application data and inadequacy of a source of direct current are the major factors limiting its use. There are many applications for motors three horsepower and below, particularly on machine tools, that require smooth braking and in many cases a Rectox copper-oxide rectifier is well suited to supply the necessary direct current.

One suggested wiring diagram for a unit consisting of control and Rectox is shown in figure 7. This scheme includes a time delay relay to disconnect the rectifier at the end of the braking period which is a feature that is not required in all cases.

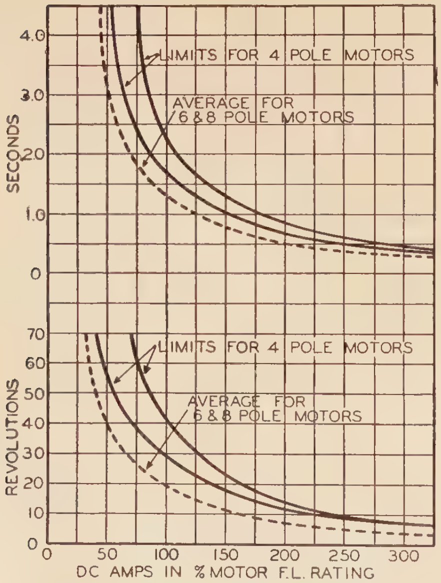


Figure 8. Performance by d-c braking

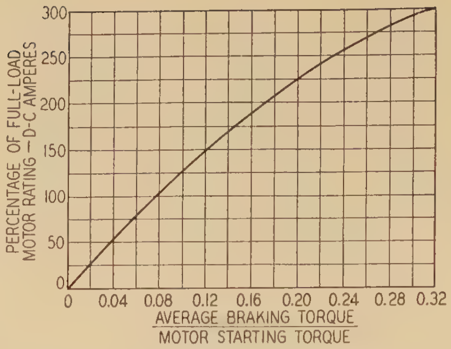


Figure 9. Required direct current for braking can be calculated by using this curve

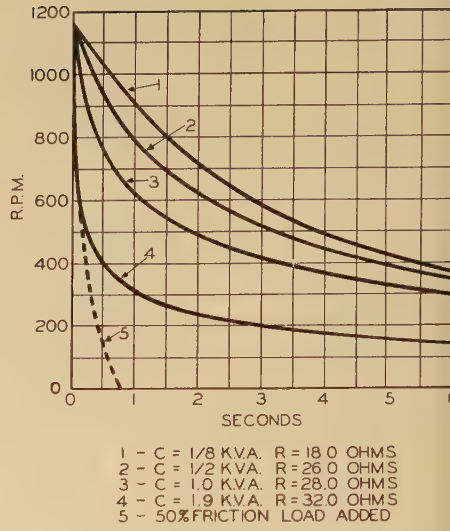


Figure 10 (right). Braking performance by capacitors and resistors

Referring to the diagram, if the "start" push button is depressed the number 1 line contactor is energized and its interlock contact bridges the "start" push button. The motor is then running, energized by the a-c power line. If the "stop" push button is depressed the circuit to number 1 contactor is broken and the a-c power is immediately disconnected. The lower contacts of the "stop" push button complete a circuit to the coil of timing relay *TR* and also the coil of number 2 contactor as soon as the normally closed contact of number 1 seals, thereby indicating that a-c power has been removed. The instantaneous make contacts of *TR* complete the holding circuit to *TR* and number 2. The contacts of number 2 apply the alternating current to the Rectox and connect the d-c terminals to one phase of the motor. The resistor in the a-c terminals of the Rectox reduces the applied a-c voltage since only a low d-c voltage is required for braking. When the cycle of *TR* expires, its time delay contacts open thereby dropping out number 2 contactor and resetting *TR*. This, of course, disconnects the rectifier but the cycle of *TR* should be made long enough to be certain that the motor has come to rest.

If a source of d-c power were available the Rectox rectifier could be omitted and the same control used except for the details of connecting number 2 contactor between the d-c line and the motor terminals. The timing relay would be required because in order to obtain effective braking a value of direct current must be applied which would overheat the motor if allowed to continually circulate while at rest.

The time and also number of revolutions required to stop a motor are plotted against direct current in per cent of motor full-load rating in figure 8. A large number of tests were made on motors ranging from one-quarter to ten horsepower, four, six, and eight poles. In studying the results of tests made on these ratings it was found that motors of like number of poles performed very similarly, particularly on the part of the curve having the most practical use. The minimum and maximum performance for the group of four-pole motors is plotted and designated as limits in figure 8. Limits were shown for four-pole motors only and the average for six- and eight-pole motors in order to eliminate unwarranted confusion of the curves.

The results shown by figure 8 pertain to motors not connected to a load and, of course, represent a wide range of windings and rotor inertia. In order to present data which could be used to predict the time or revolutions to stop a motor connected to a load (of which the friction and WR^2 is known) the variable factors which enter into motor design must be separated. The problem can be simplified by obtaining the average decelerating or braking torque throughout the decelerating period by test results. There is also a close relationship between the braking torque per ampere obtained and the motor starting torque. With this method of approach as a basis the curve of figure 9 was obtained. It is significant to note that although figure 9 again represents the average of a wide range of motor ratings there was no individual design of standard squirrel-cage motor that departed from the average curve more than ten per cent, which is a sufficiently close check for practical applications.

Figure 9 can be used to calculate the required direct current to obtain the desired braking effect by knowing, (1) the friction and WR^2 of the connected load, (2) the WR^2 and starting torque of the motor and preferably, (3) the stator resistance of the motor. The average decelerating torque to stop the motor and connected load is readily calculated from the formula given at the close of the section on friction brakes. Knowing the motor starting torque the ratio of

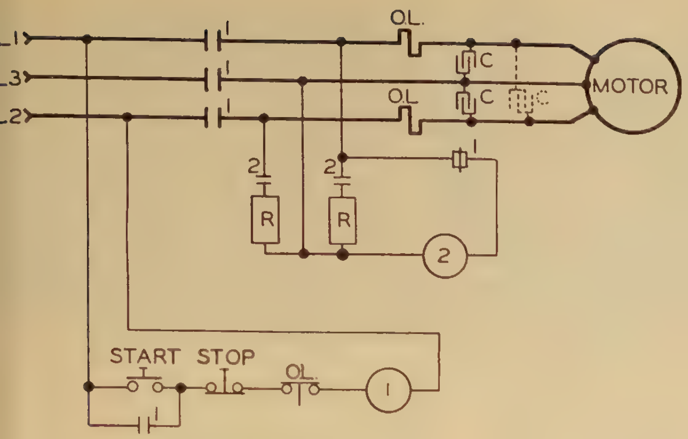


Figure 11. Schematic diagram of control for capacitor and resistor braking

verage braking torque divided by motor tarting torque can be obtained and figure) applied to get the direct current required for effective braking. If the notor stator ohmic resistance is known he resultant direct voltage can be figured nd the details as to the required source f direct current easily follow.

With the exception of fractional horsepower ratings it is sufficiently accurate o assume that the motor d-c resistance s six per cent of the motor rated voltage livided by its full-load current. Fractional horsepower windings vary considerably and may depart from this rule py so much as 500 per cent. Consequently, care must be used to obtain xact winding data before proceeding vith each application.

From inspection of the data presented n figure 8 and comparing this performance with figures 3, 4, and 6, it can readily pe seen that it is impossible to stop a notor as quickly by means of d-c braking s by means of full voltage plugging, but he former does approach the effectiveness of a magnetic brake.

While test data show that maximum leceleration is not obtained until the direct current is increased to about 350 er cent of the motor rating, experience as shown that 250 per cent is sufficient n most cases and that the difference in raking effectiveness between these values annot be noticed without equipment set p to make accurate measurements. There are numerous applications where atisfactory braking can be obtained by sing direct current of only 150 per cent f the motor rating.

This scheme of stopping a motor is ommonly referred to as "dynamic raking" but the term is not strictly true nd it is not at all similar to dynamic raking of a d-c motor. While there is decrease in braking torque as the speed reduced, it does not fall to zero and definite braking torque is applied with the rotor at standstill. Sufficient torque is available at low speed to prevent excessive coasting and the motor is stopped smoothly without the violent shock characteristic of a magnetic brake in particular.

Dynamic Braking, Using Capacitors and Resistors

Any induction motor will function as an induction generator provided it is operated in parallel with apparatus that will supply a leading power factor load since this is the only way by which an induction machine can be excited. Usually, synchronous machines supply the leading power factor but capacitors meet the requirement equally well if connected across the terminals of the machine.

While this method of stopping a motor does not possess many practical advantages it is sufficiently interesting to deserve brief mention.

Either two single-phase or one three-phase capacitor unit may be connected across the motor. The number 1 contactor starts the motor by depressing the "start" push button. The number 2 contactor connects the resistors across the motor terminals when the "stop" button is depressed. The coil of number 2 contactor is chosen to hold number 2 contacts closed to as low a voltage as possible. Since there is very little braking torque below one-third speed there is no point in attempting to hold number 2 contactor closed below this value.

A family of deceleration curves taken with a 2-horsepower 6-pole 220-volt 3-phase 60-cycle frame *W*-225 squirrel-cage motor are shown in figure 10. These curves are motor revolutions per minute plotted against time and therein differ from the type of curves so far presented in this paper.

Because of the inherent characteristic of dynamic braking to become less effective as the speed decreases this method of stopping a motor is useless if the motor is not coupled to a load having some friction. The dotted curve of figure 10 shows how the lower curve (C = 1.9 kva, R = 32 ohms) would be changed if the motor were connected to a drive having a frictional load equal to 50 per cent of the motor full-load torque rating. In this case the motor is brought to rest in about three-fourths second.

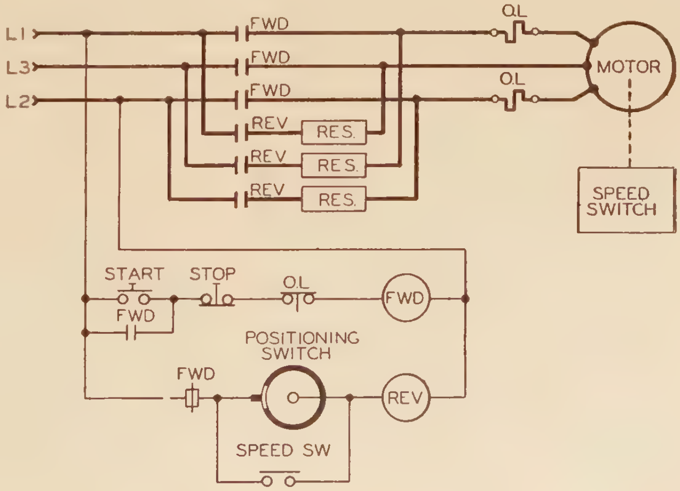
The only possibility for a practical application of this method would be when capacitors would be desirable for power-factor correction. For instance, a capacitor value sufficient to produce reasonably effective braking would result in a circuit power factor of approximately 35 per cent leading when the motor operated at about full load.

Special Applications

Examples of a few unusual applications are given below for the purpose of illustrating factors leading to the choice of one or more methods for braking a motor.

The diagram shown in figure 12 is a drive for a machine in which it was desired

Figure 12. Schematic diagram of special reduced-voltage control



to stop the motor in a given position of a rotating shaft. Reduced voltage plugging was chosen for the application. The positioning switch was direct connected to the shaft to be positioned. Its design was such that a circuit is closed through the switch except for a few degrees of rotation. The speed switch is a centrifugal switch driven from the motor and its contacts are closed from normal down to about 15 per cent speed. Below this speed its contacts are open. The stopping function of this drive is to plug the motor by reduced voltage until the speed decreases to 15 per cent. Below this speed the motor is plugged through the positioning switch until the "dead" zone of the switch is reached. Power is then disconnected and the motor may or may not coast to a stop within the desired zone. If it coasts until the switch recloses the motor is energized through the resistors to rotate the shaft until it again reaches the "dead" zone of the positioning switch.

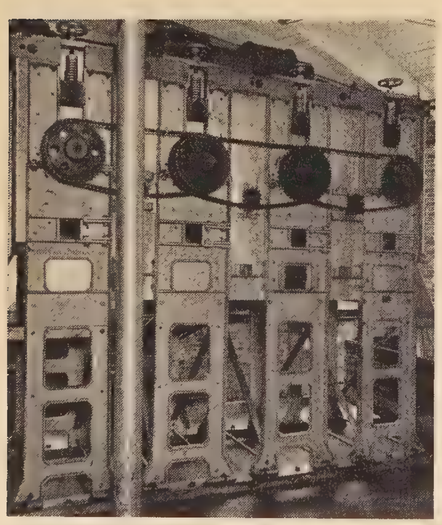


Figure 13. Application of oversized magnetic brake

Reduced voltage plugging was selected for this scheme for two reasons: (1) Plugging offered a means by which the motor was kept rotating, with power applied, until it finally stopped in the proper position; (2) reduced voltage plugging was necessary so as to limit the motor torque. Otherwise, the rate of acceleration or deceleration would have been so great as to make it impossible to stop close to a desired position.

The drive illustrated in figure 13 is installed in a plant in which the voltage regulation is poor. It was desired to stop the motor as quickly as possible after tripping an emergency stop switch. Poor voltage regulation would have defeated the effectiveness of full-voltage plugging. The problem was solved by using a magnetic brake rated 200 per cent of the motor torque. A two-pole master stop switch was used for the control circuit. One pole was wired into the motor contactor circuit and the other pole directly in the magnetic brake coil circuit. Consequently, when the stop switch was tripped the brake was applied by the time the contactor interrupted the motor line current, with the result that very effective braking was obtained.

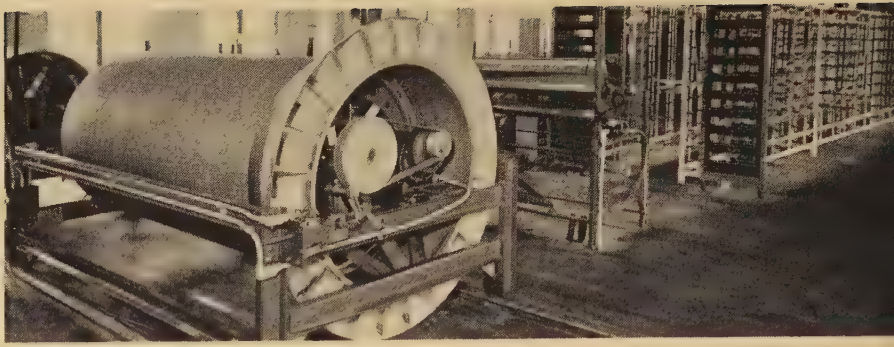


Figure 14. Application employing both plugging and magnetic brake

Figure 14 shows a drive for which the load has a WR^2 of many times the motor inertia. The drive between the motor and load is by gearing and V belts. Since several times full-load motor torque would be required to produce the desired braking it is obvious that the drive would be stressed severely if a large brake were placed on the motor shaft. It is also true that a brake on the load side would impose a peak load on the drive because of the motor WR^2. The solution chosen was to put a magnetic brake on the load and use full voltage plugging on the motor. The brake was applied so as to make the rate of deceleration of the load approximately match the motor and thereby reduce the stress on the drive as much as possible. Considerable operating experience has proved that this is a very satisfactory scheme.

Comparison of Methods

Cost

While accurate cost comparisons cannot be made because of the many factors which influence the required apparatus, the following may serve as a rough reference. In each case the cost of complete equipment, exclusive of the motor, is included and allowance for the installation of the parts is made.

The least expensive method is a solenoid-type magnetic brake and is consequently taken as a 100 per cent bas price.

Full-voltage plugging can usually b installed for about 135 per cent of th brake cost. Reduced voltage pluggin will cost about 200 per cent.

Dynamic braking with direct curren including a Rectox rectifier will be between 150 per cent and 250 per cent o the brake cost depending upon the dut cycle. If a source of direct current i available and the Rectox therefore omitted, the cost of this scheme can be reduced to about 125 per cent.

Dynamic braking using capacitors an resistors will be about 250 per cent for 22 volts and 200 per cent for 440 or 55 volts.

Magnetic Brakes

Advantages. The magnetic brake i the least expensive scheme to install an while it is not the fastest method fo stopping a motor it is second in thi choice. No power is taken from the lin during the braking period and consequently braking is independent of voltag failure.

Disadvantages. Frequently there i not sufficient space in which to mount a magnetic brake. On applications tha start and stop frequently a certai amount of maintenance is always necessary. Furthermore, the person adjustin the brake must be skilled in this or els the brake operation will not be satisfactory. There is a continued consumption of power from the a-c line whil the motor is running. If it is desired t manually rotate the motor when power i disconnected special arrangements mus be made to either electrically or mechanically release the brake. The torque of a friction brake increases considerably a very low speed which results in a rathe violent shock as the motor is brought t rest. For some applications this may b a disadvantage.

Plugging

Advantages. Full-voltage plugging wil stop a motor quicker than any othe method provided the power supply is adequate. This scheme is not very much more expensive than a magnetic brake and requires only a normal amount of maintenance. Reduced voltage plugging is a flexible method in that the rate of deceleration may be readily adjusted after installation.

Disadvantages. Plugging, even at reduced voltage, requires more than the motor full-load current taken from the line. If voltage fails the motor will coast instead of stopping quickly. A plugging switch must be mounted, driven from or otherwise coupled to the motor shaft and properly adjusted. Special care in the choice of apparatus must be considered if the application disallows a possibility of the motor rotating slightly in the reverse direction.

D-C BRAKING

Advantages. This method of stopping a motor does not require any apparatus mechanically coupled to the motor shaft nor is any maintenance required (other than is common to control apparatus). Because of this it is particularly useful on applications subject to frequent starting and stopping. The motor cannot run backwards as may occur if plugging is used and the switch improperly adjusted. The motor is free to be rotated manually at the termination of the braking period and the braking is particularly smooth. If a separate source of power is available braking will be independent of failure of the a-c supply. The separate source may be direct current or another a-c supply independent of the main a-c lines.

Disadvantages. The chief disadvantages of this scheme is its cost relative to a magnetic brake. While this scheme ranks third in its ability to stop a motor most quickly, it is often adequate for a large majority of applications. There can be no braking torque when the main a-c supply fails unless a separate source of power is available from which braking may be obtained.

DYNAMIC BRAKING WITH CAPACITORS

Advantages. This method offers the advantage of power factor correction while the motor is running and braking is independent of voltage failure of the supply line. Maintenance would be less than for any other scheme of braking the motor.

Disadvantages. Unfortunately, this scheme is a poor fourth in braking effectiveness and at the same time is about the most expensive. Consequently, it is not economically attractive as a means for braking an a-c motor.

Conclusion

In conclusion, the following suggestions should aid in selecting the best method of braking:

1. If the most important consideration is stopping the motor as quickly as possible:

(*a*) Determine if the source of supply is capable of delivering at least six times the motor full load current without dropping the voltage at the terminals of the motor more than five per cent. If the supply is adequate use a full voltage plugging controller.

(*b*) If the supply is inadequate use a magnetic brake rated 150 per cent to 200 per cent of the motor full-load torque and a control designed to open the brake coil separately from the motor winding.

2. If the most important consideration is availability of normal braking even with the failure of the main a-c supply system:

(*a*) A magnetic brake is usually employed in such cases.

(*b*) Dynamic braking using direct current is equally as good as a magnetic brake if a separate source of direct current is available. It may be worthy of consideration if the separate source is alternating current in which case a rectifier would be used.

(*c*) Dynamic braking using capacitors would meet the requirements providing a very quick stop were not necessary.

3. If the most important consideration is ability to withstand frequent operation without undue maintenance:

(*a*) A magnetic brake will require the largest amount of maintenance of any method of braking.

(*b*) Dynamic braking using direct current is the most attractive scheme both from the point of view of freedom from maintenance and least shock to the drive.

(*c*) Full voltage plugging can be used if the power supply is adequate and the motor applied so as to withstand the heating that results from frequent plugging. Some maintenance of the plugging switch and magnetic contactors will be required.

4. If the most important consideration is a smooth stop without shock to the drive:

(*a*) Dynamic braking using direct current is highly recommended for this application.

(*b*) Dynamic braking using capacitors would produce a smooth stop and may possibly deserve consideration.

5. If the most important consideration is assurance that the motor will not rotate backward:

(*a*) A magnetic brake or d-c braking are equally good in this respect as neither can result in backward rotation.

(*b*) While it would not be correct to state that plugging could not be used for such an application, it is true that this method is more subject to reversal than any other and extreme care should be used in the selection and adjustment of the plugging switch.

6. If the most important consideration is freedom of the motor to be rotated manually without the application of power:

(*a*) Dynamic braking using direct current presents no complications for such an application.

(*b*) Plugging can be used with some limitations. A friction type of plugging switch cannot be used, because manual rotation of the motor will cause the plugging switch to energize the control and apply power to the motor (unless a special control is designed to prevent this). A centrifugal type of plugging switch can be applied if the speed when rotated manually is below the minimum point at which the switch will close its contacts.

(*c*) Dynamic braking using capacitors would be applicable and may possibly deserve consideration.

The Application of Capacitors for Power-Factor Correction in Industrial Plants

By C. E. H. von SOTHEN

WHILE a paper on this subject before an AIEE meeting seems rather superfluous, perhaps a review of some of the facts to be considered in the application of capacitors to industrial loads will bring out a discussion that will be beneficial to all.

Greater interest has been shown in this subject during the past few years, both because of the wider application of power rates having some form of power-factor clause, and because of the reduction in power costs to the industrial customer, if the power factor is corrected. The utility companies generally have urged those customers who may benefit by power factor correction, to install the necessary equipment and in some cases have recommended the amount of corrective capacity to meet the conditions existing. The manufacturing companies have, of course, also made a great many surveys, each case being worked up individually to determine the amount of correction which will provide greatest return on investment.

A capacitor or static condenser consists principally of metal foil and paper insulation in a metal container and generally assembled in a rack or housing for indoor or outdoor service.

Data Required

The data required to make proper ap-

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plication generally should include the following:

1. Magnitude and power factor of the load, both maximum and average.

2. Character of the load; constant or variable?

3. Statement of power rate.

4. Is metering on high or low side of step-down transformers?

5. Are the feeders within the plant of ample capacity or are some overloaded?

6. Rating of the transformers. Are they owned by the utility company or by the industrial company?

7. Will an indoor or outdoor capacitor equipment be more satisfactory?

8. Voltage of circuit (normal and maximum).

9. Is any additional load being considered?

10. What are the atmospheric conditions at proposed capacitor location? Are they normal or are dust, corrosive fumes, and so forth, present?

11. What is the maximum ambient temperature?

Standard Types Available

It might be well to discuss briefly the various types of capacitor equipments available for industrial applications. There are four general types for use as follows:

1. The enclosed dust-tight capacitor unit for connection to individual motors or small groups of motors rated 230, 460, or 575 volts. These may also be combined in racks to make up a dust-tight equipment.

2. The small rack capacitor for indoor installation, for use at 230, 460, 575, 2,300, 4,000, and 4,600 volts, at one or several points in a plant. This design fulfills practically all industrial-plant requirements and affords maximum economy with reference to reduction of line loss.

3. The pole-type outdoor capacitor, corresponding to the indoor small rack for 2,300, 4,000, and 4,600 volts. This can be either mounted on a pole or bolted to a foundation.

4. The large rack equipment for either indoor or outdoor installation, for improving power factor of a large block of power at one point, on circuits of from 230 to 6,900 volts.

There have been a few installations of automatically controlled capacitors to maintain approximately constant power factor, reactive kilovolt-amperes, or current of some predetermined value. These depend upon some form of master relay which opens or closes oil circuit breakers or contactors controlling several blocks of capacity. The advantage is that a higher average value can be held without going too far leading at light loads. Whether such an equipment will prove economical depends, as usual, upon the power contract.

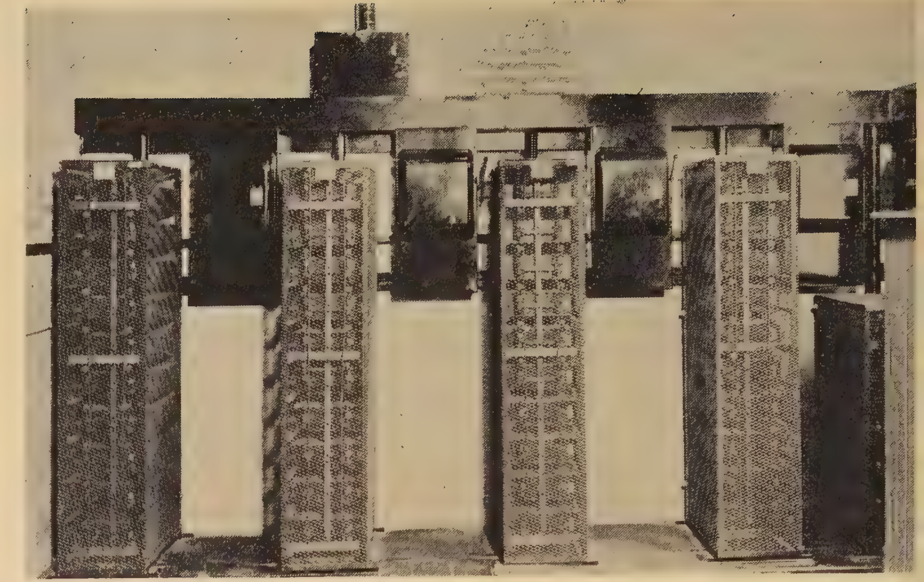

Figure 1. Four 100-kva and one 60-kva 3-phase 60-cycle 460-volt indoor small rack capacitors

The foregoing covers the types available. Now how should they be applied?

The manner in which the problem is approached to meet conditions imposed by various classes of rates may be illustrated best by a few typical examples from various parts of the country.

Calculations

Case I

The power contract contains the following rates and provisions:

Rate: (per month)
Demand charge:
  $1.25 net, per kilowatt of maximum demand for the first 500 kilowatts of demand
  $1.00 net, per kilowatt of maximum demand for all over 500 kilowatts of demand
plus
Energy charge:
  1.5¢ net, per kilowatt-hour for the first 10,000 kilowatt-hours
  0.9¢ net, per kilowatt-hour for all over 10,000 kilowatt-hours
Minimum charge:
  The demand charge.
Special provision:

(*a*) When customer's power factor is less than 80 per cent or more than 90 per cent, the billing demand shall be increased or decreased in the ratio that 85 per cent bears to the actual power factor. The power factor shall be determined monthly by computation from the registration of active and reactive watt-hour meters.

In this case power was supplied at 6,900 volts, 3 phase, 60 cycles. There was ample transformer capacity and none of the 230-volt feeders was overloaded. Therefore only primary capacitors were considered, for installation in the main switch-board room.

The power bills for one year were used as a basis for calculations. A typical month showed the following:

Actual demand..........	1,056 kw
Power factor............	60 per cent
Reactive kilovolt-ampere hours.................	277,600
Kilowatt-hours..........	208,800

All figures were based on a rack large enough for 540 kva, but containing various numbers of units as an initial installation, starting with 495 kva. Indications were that additional capacity would be required in the future.

The 495-kva equipment would have to operate during the month in question only 560 hours to average 100 per cent power factor, but let us say 625 hours. The billed demand would be 85 per cent of 1,056 or 898. The loss on this equipment would not exceed 1.65 kw but say 2 kw which would increase the demand to 900 or a net saving in demand of 156 kw. This at $1.00 per kilowatt amounts to $156 saving in demand charge.

The loss of 1.65 kw for 625 hours at 9 mils amounts to $9.30 or say a net saving in the power bill for the month of $146.

Each month was figured similarly and the total annual saving on the power bill amounted to $1,804. The equipment had a first cost of $5,667 and an installed cost of $6,060. Carrying charges may be taken as nine per cent of $5,667 or $510. (Interest is omitted since the purpose of the calculation is to determine the return on the investment.) The net annual saving is then $1,294 or a return of 21.3 per cent on the investment of $6,060.

Other sizes were figured and the result was the recommendation of a 540-kva rack containing 360 kva in units. This showed a return 27.8 per cent on an investment of $4,700.

Of course if a 360-kva rack could have been used, the initial cost would have been lower and the return would have been greater.

CASE II

The power rates in this case were as follows:

Demand—First 100 kva	$3.00 per kilovolt-ampere
All in excess	$1.50 per kilovolt-ampere
Energy—First 200 hours use of kilowatt demand per month	$0.007 per kilowatt-hour
All over 200 hours	$0.005 per kilowatt-hour

As the kilovolt-amperes would never be reduced below 100, all savings were at $1.50.

Power was supplied at 13,200 volts and stepped down to 480 volts. As this was a grain mill, dust-tight equipment was required. From billing data for the year 1936 it was found that the average was 611 kva demand, 455 kw, 74.5 per cent power factor, and 408 kva lagging reactive.

Figure 2. Forty-kva 4,000-volt 3-phase 60-cycle pole-type capacitor

As the corrective kilovolt-amperes of a capacitor varies as the square of the voltage, a 210-kva 460-volt equipment will provide 229 kva leading. This reduces the reactive to 179 and kilovolt-amperes to 489, or a saving of 122 kva per month. For 12 months at $1.50 per kilovolt-ampere, the saving in demand is $2,196. The loss on this equipment would not exceed 0.76 kw which for 16 hours per day and 300 days per year at $0.005 per kilowatt-hour would amount to $18.24 per year. The net saving on the power bill would therefore be $2,177.76 per year.

A 210-kva 460-volt dust-tight capacitor equipment had a first cost of $2,103 and estimated installed cost of $2,313. Carrying charges were taken at nine per cent or $208 so that the net annual saving would be $1,970 which represents a return of 85.1 per cent on the investment of $2,313.

Other sizes were calculated similarly with the results shown in table I.

While the 180-kva equipment shows a greater per cent return, the extra investment for the 210 kva would be paid for in two years. The same might be said for the 240 kva over the 210-kva equipment, but it was found that the 240-kva equipment would correct the power factor to 99 per cent at time of maximum demand for some months, which would mean leading power factor on average loads. The 210-kva equipment was therefore installed.

CASE III

While this case involves a rather small installation, it illustrates another form of power contract which may be of interest.

Monthly Demand (Kilowatts)		Demand Charge (Dollars)
First	10 or less	30.00
Next	15	2.50 per kilowatt
Next	25	2.00 per kilowatt
Next	50	1.50 per kilowatt
Next	1,900	1.25 per kilowatt
Next	2,000	1.00 per kilowatt
All over	4,000	0.90 per kilowatt

Monthly Use (Kilowatt-hours)		Energy Charge (Cents per Kilowatt-hour)
First	1,000	2.5
Next	1,500	2.0
Next	2,500	1.5
Next	5,000	1.0
Next	190,000	0.85
Next	300,000	0.75
All over	500,000	0.65

Special Provisions. The service supplied by the company shall be taken by the consumer whenever possible at an average power factor of not less than 70 per cent lagging. If the service is taken at an average power factor of less than 70 per cent lagging, then the demand for billing purposes, in lieu of the measured demand, shall be taken as the product of the measured demand and the quotient resulting from dividing 70 per cent by the actual average lagging power factor expressed in per cent. If the service is taken at an average power factor of more than 85 per cent lagging, then the demand for billing purposes, in lieu of the measured demand, shall be taken as the product of the measured demand and the quotient resulting from dividing 85 per cent by the actual average lagging power factor expressed in per cent.

Figure 3. Three hundred-kva 460-volt 3-phase 60-cycle large rack capacitor

The average power factor for the month shall be determined by computation from the registration of an active watt-hour meter and a reactive watt-hour meter. It shall be the quotient resulting from dividing the registration of the active watt-hour meter by the square root of the sum of the square of the registration of the active watt-hour meter and the square of the registration of the reactive watt-hour meter.

As there was a detent or ratchet on the reactive watt-hour meter, nothing could be gained by operating at leading power factor during light-load periods.

In this case the primary voltage was

Table I

Capacitor Rating (Kva)	Corrected Power Factor	First Cost	Installed Cost	Net Annual Saving	Per Cent Return on Investment
150	90	$1,548	$1,703	$1,526	89.5
180	91	1,817	2,000	1,800	90.0
210	93	2,103	2,313	1,971	85.1
240	95.5	2,463	2,709	2,147	79.0

4,000 and plant voltage 230. As several circuits were rather badly overloaded, secondary capacitors, distributed over some of the branch circuits, presented definite advantages over an installation on the primary side. Furthermore, conditions were such that a primary capacitor would have to be installed outdoors, adding to its cost.

Table II

Month	Kilowatt-hours	Reactive Kilowatt-hours	Demand Read	Power Factor	Demand Billed	Penalty @ $1.25
August	25,200	38,200	124	55	158	$43 00
September	23,940	35,560	141	56	176	43.75
October	22,540	32,900	121	57	149	35.00
November	21,280	29,120	136	59	161	31.25

Billing for only four months was available, on which to base calculations, but results have indicated the assumptions to be correct. These were as shown in table II.

The plant was operating 16 hours per day and 5 days per week with the following results:

Month	Average Kilo-watts	Average Reactive Kilovolt-amperes	Corrective Kilovolt-amperes Required	
			For 72 Per Cent Power Factor	For 87 Per Cent Power Factor
August	71.5	108.5	39.5	68.0
September	71.3	106	34.0	66.0
October	67.0	98	34.0	60.0
November	60.5	82.8	25.0	49.0

The values of 72 per cent and 87 per cent were taken rather than 70 per cent and 85 per cent to allow some margin for changes in conditions. The first value is necessary to avoid the penalty and the second is required if a bonus is to be earned.

It is evident that a 40-kva capacitor will correct each month to 70 per cent or better. What will be its effect in November?

Forty kva for 22 days and 16 hours per day or 14,100 reactive kilovolt-ampere-hours leading. This leaves a net of 15,020 reactive kilovolt-ampere-hours lagging which combined with 21,280 results in an average power factor of 82 per cent; not sufficiently high to earn the bonus.

To determine the effect of a 70-kva equipment, consideration must be given to the fact that for a few hours each day, the power factor may be leading, and with the "detent" on the meter the result is the same as unity power factor. By checking the active and reactive meters carefully and obtaining a record of demands, it was found that during working hours, the load never dropped below 35 kw at 55 per cent power-factor or 53 reactive kilovolt-amperes. From demand-meter records for the four months it was found the power factor with a 70-kva equipment would be leading for one hour per day in August and September, two hours in October, and three hours in November and it was assumed the leading kilovolt-amperes would be 70 minus 53 or 17 kva. Therefore, the effect would be as follows for August:

$$\begin{array}{l} 70 \times 22 \times 16 = 24{,}640 \text{ reactive kva} \\ 17 \times 22 \times \ \ 1 = \ \ -380 \\ \hline \qquad\qquad\qquad\quad 24{,}260 \text{ reactive kva} \end{array}$$

$$\begin{array}{l} 38{,}200 \text{ reactive kva} \\ -24{,}260 \\ \hline 13{,}940 \text{ reactive kva} \end{array}$$

$$\frac{R}{KW} = \frac{13{,}940}{25{,}200} = 0.554$$

or 87.5 per cent power factor

Similar calculations for the other months gave these results:

September 88.5 per cent
October 91.5 per cent
November 96.5 per cent

The effect of the 40-kva equipment would be to avoid the penalty or a saving of $153 for four months or approximately $459 per year.

This equipment consisting of 8 5-kva 230-volt enclosed units with hangers and with fuses and dischargers would have a first cost of $728 and installed cost of $800. The net annual saving with nine per cent carrying charge would be $393 representing a return of 49.1 per cent on the investment of $800.

With the 70-kva equipment the penalty would be avoided and bonus earned each month. For example in August, the billed demand would be

$$124 \times \frac{85}{87.5} = 121$$

or a saving of 37 kw over the demand as actually billed (158 kw). For September this would be 41 kw, October 36 kw, November 41 kw, at $1.25 per kilowatt these total $193.75 or approximately $581.25 per year.

A total of 14 5-kva 230-volt enclosed units had a first cost of $1,274 and installed cost of $1,400. The net annual saving with nine per cent carrying charge would be $466 or a return of 33.4 per cent on the investment of $1,400.

Because of the greater return from the 40-kva equipment and the fact that conditions were somewhat uncertain, this equipment was recommended with the suggestion that a further study be made at a later date, with the possibility of installing additional units.

Protection

The problem of protecting capacitors and lines is similar to that on any electric system involving a relatively large number of pieces of apparatus fed from a common source. In rack and pole-type equipments the entire group of units is fed through one circuit-interrupting device, which is generally set to trip at twice normal line current. Therefore, many times normal current of an individual unit could flow into a fault within

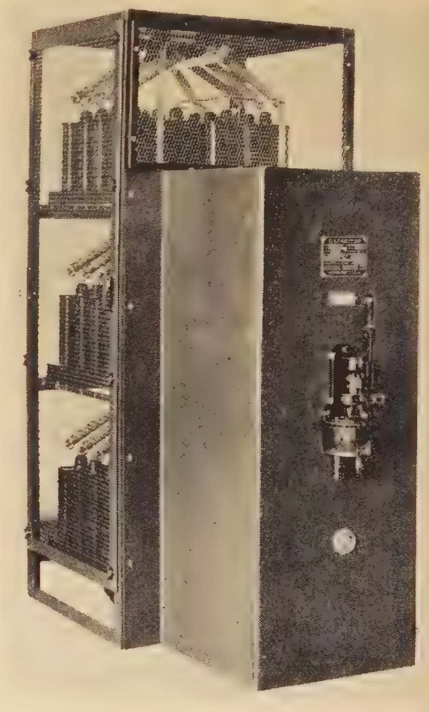

Figure 4. Two hundred forty-kva 4,600-volt 3-phase 60-cycle indoor large rack capacitor

the unit without opening the line circuit breaker. Individual fuses, however, will limit the amount of energy dissipated within a capacitor unit case by quickly clearing the fault and without interrupting power supply to the remainder of the equipment.

When a capacitor is disconnected from the line, electrical energy remains stored within the unit. All types of equipment must therefore be provided with means for draining the energy after the circuit has been opened. A discharge device should always be provided by the manufacturers as part of standard equipment.

A circuit-interrupting device of some form should in general, be used with capacitors to serve as a main switch as well as to provide overcurrent protection. As standard capacitors are designed for a permissible working voltage approximately 15 per cent in excess of rated voltage, and to provide for extra current due to possible harmonics, the main switch should have a capacity of at least 35 per cent over rated current of the capacitor.

In some cases, on 230-volt circuits, economies may be effected by using 460-volt capacitors and autotransformers, because of the lower cost per kilovolt-ampere of 460-volt capacitors. Since the capacitor is capable of handling a maximum of 135 per cent of normal kilovolt-amperes, the transformer output rating should be selected accordingly.

The possible short-circuit current at the installation should, of course, be considered when selecting the interrupting device. The circuit breaker selected must be able successfully to clear the maximum short circuit that may occur at that point.

Indoor installations of capacitors ordinarily do not require special consideration in regard to lightning protection. If the secondary circuit to the consumer presents any appreciable exposure the lightning arrester ordinarily installed to protect the consumer's apparatus will provide sufficient protection for the capacitors.

Outdoor capacitors should be protected by distribution-type lightning arresters, except where existing lightning arresters on the circuit are sufficiently close to the point of installation to provide protection.

Effects of Low Power Factor

The question of point of application of the capacitor is usually one of economics. The greatest benefit, from the electrical standpoint, can be derived from capacitors connected directly at the motor terminals, since they reduce power losses in all lines and transformers between the power source and the motor. However, such capacitors usually have a higher cost per kilovolt-ampere than equipment installed in larger blocks at the bus or on the primary feeder. The higher cost of low-voltage units must be weighed against the cost of a primary equipment plus additional copper for the low-voltage feeders, if some of these are overloaded or voltage drops are excessive. Also improvement in voltage obtained by capacitors on the low-voltage transformer secondaries, may warrant the higher first cost of a low-voltage installation.

Figure 5. Three hundred-kva 4,000-volt 3-phase 60-cycle outdoor large rack capacitor

It is often found that no more load can be added to a circuit because the wattless current has overloaded the system. By improving power factor, more load can be added at a lower over-all cost than would be incurred by installing more copper or additional circuits.

Low-power-factor conditions in a plant produce low voltage and excessive dips upon overloads and peaks. Starting and running torques of motors are reduced in proportion to the square of the voltage. Motors start slowly or not at all and may be stopped on voltage dips through action of the undervoltage device. The slip of induction motors is greater at reduced voltage, hence production suffers.

Of course, if the transformer bank is overloaded low-voltage capacitors will easily prove themselves out in comparison with additional transformer capacity.

A point which is sometimes overlooked or misunderstood when considering the effect of capacitors on an industrial load, is the fact that although the power factor of a motor is higher at full load than at part loads, the reactive kilovolt-amperes are also higher. Therefore to raise the power factor to unity requires slightly greater corrective kilovolt-amperes at full load than at part load. For example the full-load power-factor of a 10-horsepower 1,800-rpm squirrel-cage motor is 89 per cent and the lagging reactive kilovolt-amperes is 4.5 At half-load the power factor of this motor is 75 per cent and the lagging reactive kilovolt-amperes 3.9.

The thought is quite frequently expressed that, to meet certain conditions, capacitors should be installed on a motor to reduce starting current. When consideration is given to the fact that the full-voltage starting current of a normal-torque low-starting-current squirrel-cage motor is $4^1/_2$ or $5^1/_2$ times normal and its power factor at start may be 40 per cent or lower, it is readily seen that an unreasonable amount of capacity is required.

If starting current is important, the wound-rotor motor offers a better solution to the problem.

If power is generated instead of purchased, it may be necessary to improve power factor to relieve overloaded feeders or an overloaded generator. Most generators are rated on the basis of 80 per cent power factor. Therefore, unless the prime mover is oversize, there is little to be gained by raising the power factor above 80 per cent. For example, if a 500-kw 625-kva 80-per cent-power-factor generator is actually carrying 450 kw at 60 per cent power factor or 750 kva, and if the prime mover is capable of driving the generator with a 550-kw load a capacitor may at first be installed simply to bring the current within the rating of 625 kva. This would take 170 kva. Later, to provide for expansion extra units may be installed.

Assuming the additional load would also be at 60 per cent power factor, it would require 280 kva additional to reduce the total kilovolt-amperes to 625 with a 550-kw load. The corrected power factor would be 88 per cent. Whether the industrial company purchases or generates its power, a power-factor study is warranted because savings may be possible which may far exceed the cost of corrective capacity required.

Multiple Lightning Strokes—II

By K. B. McEACHRON
FELLOW AIEE

THE multiple stroke has been defined as a succession of discharges in substantially the same path, either between clouds or between cloud and ground. Multiple strokes are of considerable interest to the engineer, because of the possible effects of successive application of impulses to equipment with a very small cooling or resting period interposed. The author has undertaken studies of natural lightning in three different locations with three somewhat different methods, one of the objects being in each case the determination of characteristics of multiple strokes. One of these investigations is a detailed study of lightning strokes to the Empire State Building in New York, another in Pittsfield, Mass., employs photographic methods making use of an observatory erected for the especial purpose of studying lightning, and the third is an investigation of multiple strokes to transmission lines as measured by the use of the especially designed crater lamp oscillograph installed and operated in co-operation with the American Gas and Electric Company at Roanoke, Va.

These three investigations have all been in operation for three or more lightning seasons, but because of the large amount of data obtained from the other investigations, it will be necessary to confine the present paper to the results obtained in Roanoke, although naturally the results from the other investigations will influence the point of view.

Photographs showing the multiple character of some strokes of lightning have long been in existence, but it seemed to be important to find out how many of these effectively applied successive impulses to electrical apparatus connected to transmission lines. Fortunately, the application of the expulsion protector tubes supplied a means of determining, through the use of magnetic oscillograph elements arranged to record fault currents to ground, some of the successive discharges of a multiple stroke, since the protector tube allows but one-half cycle of power current to flow following each impulse. Of course such a method does not indicate the presence of more than one discharge in any one-half cycle, and from photographs of strokes it is known that successive discharges may be as close together as a few hundred microseconds. Recognizing this situation, during one lightning season a circuit was set up with a capacitance coupling to the transmission line, in such a manner that it was hoped to superimpose any during-half-cycle impulses, but none were found. This does not indicate that they were not present, rather that the system used was not able to record them, and if they are to be recorded other methods will have to be used. It will be readily understood that on a line not equipped with expulsion tubes the continuous flow of fault current obscures the effect of successive lightning discharges.

The crater lamp oscillograph[1] was installed in Roanoke early in 1934, and connected to read fault current to ground in each of the three phase conductors of the number 1 circuit of the double-circuit 138-kv Roanoke-Glenlyn line,[2] and the fault current in phases 1 and 2 of the Roanoke-Danville line. The sixth vibrator was used to record the potential to ground of phase 1 of the Danville line. The results obtained during the first year of operation of the oscillograph were reported to the Institute in December 1934.[3] The present paper will present the results of four lightning seasons beginning with 1934.

Analysis of Results

In analyzing the 295 records obtained in Roanoke, judgment must be exercised because a flow of current on either of the two lines being studied will draw current from the other, since they are bussed together at Roanoke. This is illustrated in the typical oscillogram of figure 1, where the stroke was to the Glenlyn line. It was assumed, however, that simultaneous strokes to the same phase conductors did not occur on the Glenlyn and the Danville lines. While such an occurrence is possible, it is too unlikely to be given weight.

Obviously, the operating data of the two lines were studied carefully, and circuit breaker operations correlated with the crater-lamp-oscillograph records. The *PM*-13 oscillograph at Glenlyn recorded the fault currents flowing in both of the Glenlyn circuits, and the records were studied with engineers of the American Gas and Electric Company. The *PM*-13 records were particularly helpful in studying the performance of the number 2 circuit of the Glenlyn line, which was on the same steel towers but which was not equipped with protector tubes. Oscillograph records which did not cause power follow current through protector tubes were neglected as being too uncertain. If included, these would add to the number of single-stroke records obtained.

Although some data from the Carolina Power and Light Company were included in the 1934 paper by the author, the data in the present paper are confined to the lines of the American Gas and Electric Company.

Table I. Occurrence of Strokes

Year	Total Strokes	Single Discharges	Multiple Strokes			Number of Storms Giving		
			Number	Per Cent	Discharges	Single Strokes Only	Multiple Strokes Only	Single and Multiple
1934	42	32	10	24	44	11	3	2
1935	21	19	2	9	4	9		2
1936	45	32	13	29	38	6	1	9
1937	76	49	27	35	90	13	2	11
Total	184	132	52	28	176	39	6	24

Frequency of Occurrence

A total of 184 strokes was recorded by the crater lamp oscillograph, of which 52 are known to be multiple. Out of 69 storm days, 39 yielded 73 single strokes; 24 days gave 59 single and 42 multiple

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1. For all numbered references, see list at end of paper.

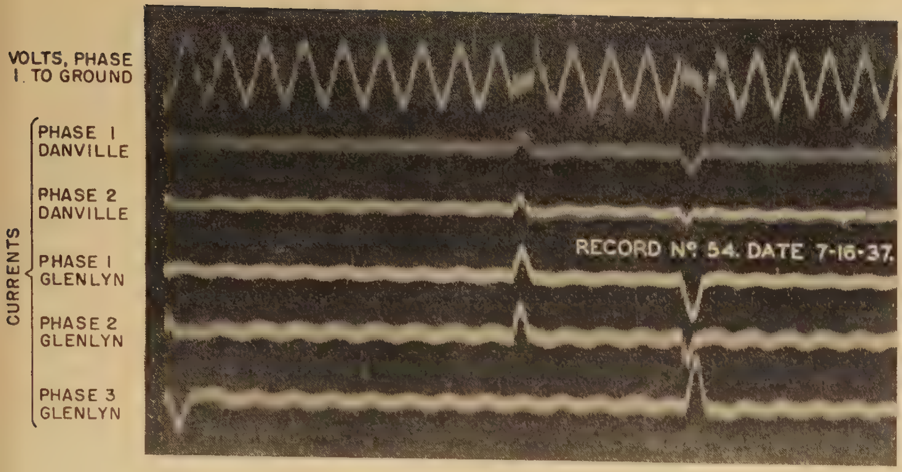

Figure 1. Crater lamp oscillogram showing operations of expulsion protective gaps on successive lightning discharges to the Roanoke-Glenlyn line

strokes; and on 6 days only, 10 multiple strokes were recorded with no single strokes. These data seem to indicate that certain storms produce few if any multiple strokes, and other storms seem to have on the average about an equal number of single and multiple strokes.

In view of the New York investigation, it does not appear strange to find some degree of similarity between strokes in the same storm as to general characteristics. Cloud formation is probably responsible for the different characteristics of lightning when one stroke is compared to another, and it is probable that the controlling conditions lie in the cloud itself. There is evidence to indicate that the same cloud center will tend to continue to produce the same type of discharge, at least while discharging to objects within a limited area.

When considering the data presented in this paper, it is recognized that great accuracy is not possible, since a certain number of single strokes are not recorded which did not cause tube follow current and multiple strokes with time intervals less than one-half cycle are not identified. In table I the data obtained are given by years.

The importance of the multiple stroke is realized when it is considered that of the discharges recorded, 176 or 57 per cent of the total discharges were multiple, or putting it another way, 28 per cent of all the strokes produced 57 per cent of the discharges.

A brief comparison with the results from Pittsfield, using a multi-lens moving-film camera will be of interest. During the years 1935, 1936, and 1937 a total of 73 storm days were recorded. Two hundred thirty-two strokes were photographed, of which 55, or 23.7 per cent, were multiple. This percentage is lower than the true number, since the photography becomes poor at distances of several miles under weather conditions often existing. The check, however, with the Roanoke data is quite good, indicating that roughly one-fourth of the strokes over a period of years consist of more than one discharge.

Multiple Stroke Data

A summary of the data obtained is given in figure 2, where each multiple stroke is plotted against its time duration in cycles (60 cycles). The maximum time duration is still as it was reported in 1934, namely, 40 cycles. Although, if enough data were available, a somewhat longer time might be found, yet other work not yet published indicated that the probable maximum time will not much exceed one second. When examining these data, it should be realized that there are many multiple discharges which will not have sufficient magnitude to cause a second tube operation, and thus would not get in the record. Thus data, on multiple strokes close by, obtained by photographic means, may differ somewhat from that obtained from an investigation of this sort even of the same strokes. There is also another point of departure, in that another stroke could occur to the ground wire within a second of time at other points and the oscillograph could not identify them as being of the same multiple discharge. This possibility, based on other observations, can be dismissed as being highly improbable in any appreciable number of cases.

Time Interval and Number of Successive Discharges

The time interval between successive discharges is important, since it has to do with the rest period afforded insulation, whether air or solid before being restressed. In figure 3 the data of figure 2 have been replotted to show the time intervals and the frequency of their occurrence per 100 discharges. The longest time was 26 cycles between discharges, while the shortest time will of course be zero cycles when current flows in two succeeding half cycles. The maximum time recorded is of considerable interest from the point of view of deionizing time of the air under lightning conditions.

In Pittsfield, the longest time between successive strokes was 0.44 second, which is slightly over 26 cycles. It might be argued that in the case of the crater-lamp-oscillograph data, a second stroke caused the record at the 26 cycle point, but the Pittsfield photographs show discharges in substantially the same path 0.44 second later, so it appears that a time as long as 26 cycles is possible.

Concerning the minimum time, nine per cent of the discharges occurred with a time interval of one cycle. Lacking means for determining shorter times, in this particular investigation no conclusion can be drawn. However, in the Pittsfield investigation, times shorter than 0.0005 second were measured between discharges.

The number of successive discharges as shown in figure 4 vary up to 12 as a maximum. Sixteen per cent of all the strokes and 61 per cent of the multiple strokes consisted of at least 3 discharges, while 4 per cent of all strokes and 15 per cent of the multiple strokes had at least 5 discharges.

One might suppose that in general the largest number of discharges would go with the greatest stroke duration, and this is true in a very general way, but

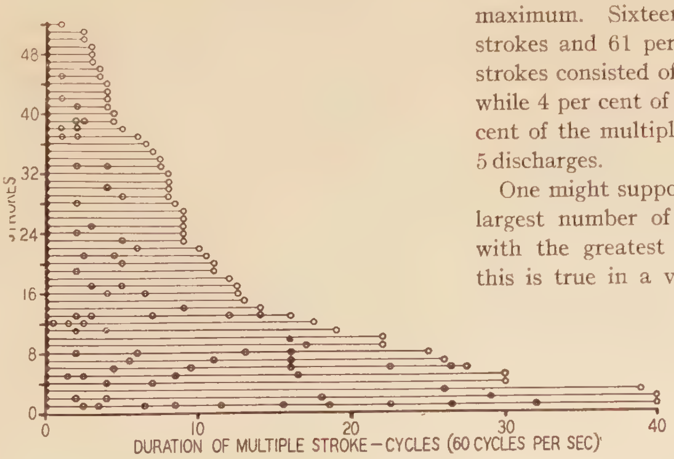

Figure 2. Distribution of multiple strokes and discharges

the data show serious exceptions since one 40-cycle stroke had 12 discharges and a 39-cycle stroke had 3, while a 6-cycle stroke had 4 discharges.

Discussion and Conclusions

This investigation indicates clearly that multiple strokes do take place to transmission line conductors and must be considered in any protection setup. Protective devices designed to protect apparatus from the effects of lightning should not include mechanical motions which take time for restoring to normal condition if proper protection is to be maintained.

In the four-year investigation, 308 discharges were recorded from 184 strokes. Fifty-two multiple strokes yielded 176 discharges. Approximately 25 per cent of all strokes were multiple. The largest number of successive discharges was 12. The longest time between the first and last discharge was 0.66 second or 40 cycles, while the shortest time is not indicated from this investigation. Other work shows a time as short as 0.0005 second.

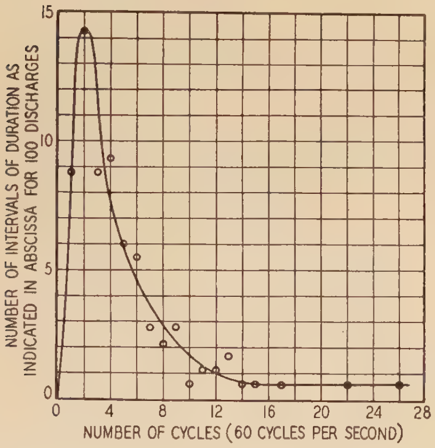

Figure 3. Time intervals between discharges in multiple lightning strokes

As to the characteristics of the successive discharges with regard to the initial discharge, little information is given, except that a study of the data seem to indicate more current is associated with the multiple stroke discharges than in general occurs with strokes having but a single discharge. There is also some tendency for the first discharge of a series to pass more current than the succeeding discharges. These observations are deduced from a study of the number of phases involved with the different discharges.

There appears to be a definite tendency for some storms to produce more multiple strokes than others. In fact as far as the records of strokes to the transmission line are concerned, more than half of the storms did not produce multiple strokes. This is probably related to the cloud structure and the disposition of charges within it.

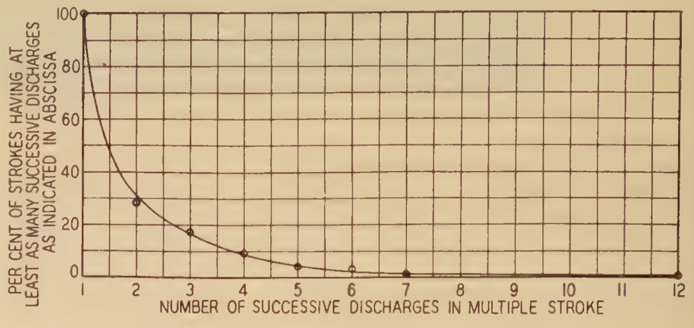

Figure 4. Number of successive discharges in multiple lightning strokes

In general, the multiple strokes which occupy the greatest time between the first and last discharges will have the greatest number of discharges, although this is not always true. The methods used could not distinguish between discharges occurring during a half cycle of protector tube follow current.

The great majority of the follow currents measured were positive in polarity indicating a negative direct stroke. This is in agreement with the work of Lewis and Foust,[4] who found that of 358 strokes recorded during the years 1934, 1935, and 1936 through tower legs of transmission lines, approximately 95 per cent were negative. Since the succeeding strokes did not show a polarity of follow current particularly different from the first discharge of the series, there seems to be no evidence which indicates a reversal of polarity as between the first and succeeding discharges, rather such evidence as there is indicates that the polarity of most discharges was probably negative.

On a line with a lower insulation level, the number of successive discharges measured in a given stroke would be greater assuming that some of the discharges did not have enough current in the discharge to raise the potential of the higher-insulated line to a point where flashover would occur. This indicates that the results given as to the number of successive discharges is probably pessimistic for low-voltage circuits where the apparatus strength may be low compared to the insulation strength of the line.

In thinking about the effects of multiple strokes upon connected apparatus, it should be remembered when the stroke takes place some distance from the station, assuming a line without overhead ground wire protection, and a line flashover occurs, only the first impulse of the series will be transmitted along the line unaffected by the tower footing resistance of the flashed structure. Succeeding discharges in the stroke will develop potentials on the line dependent upon the *IR* drop through the tower footing resistance.

Where overhead ground wires are used, and strokes do not contact the line conductors, the potential of the traveling wave, both for the first discharge and succeeding ones will be dependent upon both the footing resistance and the current in the various discharges. Under these conditions, many low-current discharges which are observed upon moving-film photographs of direct strokes would not be of serious consequence with reference to connected apparatus. It is at this point that the investigation is probably of greatest value, in that it indicates the number of successive discharges which had sufficient magnitude to cause operation of the protector tube.

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Photoelectric Weft-Straightener Control

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THE PROCESS of weaving consists of interlacing spun threads at right angles on a loom, figure 1. In the woven material thus formed, of which cotton cloth is a very common example, the lengthwise threads are designated as the "warp" and the crosswise or filling threads are designated as the "weft," figure 2.

As woven, the weft threads of fabrics are substantially at right angles to the warp threads. Numerous subsequent finishing processes involve rehandling the wet material in rope form. When finally stretched and dried, much of the cloth will not have weft and warp threads at right angles in spite of inspection and manual means for mitigating this defect. This skewed goods tends to change shape with use so that fit or hang or design does not hold up to the purchaser's expectations.

This paper describes a successful automatic means, for squaring up the goods in the final drying and stretching process, thus making it possible to raise materially the textile finishing standards in this respect.

The size of the threads and the number used per unit area varies widely. Likewise grouping, and arrangement of threads to form patterns are subject to wide variations. In general, however, it may be said thread diameters range from 0.005 inch in fine shirting to 0.050 inch in heavy duck. Also, thread counts as low as 20 per inch are used in open-weave marquisettes while in fine shirting as high as 100 per inch are frequently found. Still others use as high as 136 warp threads with 60 weft threads. Cloth is produced in a great variety of widths, ranging from 30 to 108 inches and many hundreds of feet in length.

Cloth as it comes from the loom is strong and serviceable and a limited amount of it is used as "gray goods"; another name for "unbleached cotton cloth," but most of it, some 90-odd per cent of it, is "bleached" to give it that fine white well-known appearance. The bleaching operation involves much rough handling; treatment with chemicals, subsequent washing, and in most cases starch is added to improve its appearance. Cheaper grades are also filled with talc or white clay.

In the process of finishing, the cloth must be transported from one vat to another which may be a thousand feet or more away. Transportation is usually effected by pulling the cloth in rope form from one vat to another, often over a circuitous route guided through large porcelain rings or "pot eyes," figure 3. This is harsh treatment as far as the structure of the cloth is concerned and it results in considerable distortion of the weave from the right angular relationship of the warp and weft threads so accurately woven by the loom.

Following the washing operation, the cloth is "beaten out" in a scutcher, to its original flat form, after which it passes through a starch mangle, figure 4, where the filling starch or clay is added and subsequently through drying apparatus to remove the wash water. The drying operation is accomplished with a combination of dry cans and tenter.

Dry cans consist of a series of steam heated cylinders arranged so that the cloth will pass from one to another, in contact with about three quarters of the circumference of each, figure 4. The temperature of the cans and speed of the cloth is controlled so that when leaving it contains a definite prescribed amount of moisture.

A tenter is a machine designed primarily to restore the cloth to its original width making due allowance for shrinkage, by exerting a suitable pull on the selvage edges at opposite ends of the weft threads, figure 5. Frequently tenters are enclosed in ovens and the sizing and drying operation combined either wholly or in part.

In practice, depending on the type of cloth and the finish required, the cloth may be completely dried on a tenter, or stretched to the required size on a tenter and dried on cans or partly dried on a tenter and finished on cans; but regardless of the system used, the weave distortion or skew introduced in the previous processes must be removed; e. g., the cloth must be "straightened" to make it salable.

Cloth straightness may be defined as the perpendicular relationship between weft and warp threads, also deviations from straightness may be expressed as "skew." It is very essential that cloth be straight, both in plain fabrics as well as those embodying woven patterns. Similarly cloth should be straight before being printed, otherwise, the pattern will be distorted after the cloth is cut into small pieces, such as required for curtains or wearing apparel.

The straightening operation should be performed on the cloth while it is moist as the fibers are then pliable and susceptible of proper positioning. Straightening is accomplished by moving the selvage on one side with respect to the other, an amount necessary to correct the distortion.

Several machines are now on the market for straightening cloth which perform with a fair degree of success. One of the more common is the "swing tenter" in which an oscillating movement of one chain with respect to the other is introduced which tends to "spread" the skew over the entire area, thereby reducing the magnitude of the distortion in any particular area. Strictly speaking, this device could not be classified as a "straightener," but rather one to even out the peak skews to passable limits in cloth where true straightness is not required.

In the "canting roll" type shown in figure 6, the cloth which has been previously spread to its full width is passed over two or more rolls, the ends of the axes of which are made to approach or recede from each other, thereby slackening or stretching the selvage as may be necessary to introduce the required correction.

Still another type of straightener performs the straightening operation in the tenter by advancing or retarding one chain with respect to the other so that the perpendicular relationship is secured in the cloth as it leaves the tenter. Figure 7 shows one way of accomplishing this. A differential gear is introduced in the main drive shaft by means of which the position of the left-hand chain may be advanced or retarded with respect to the right-hand chain by adding or subtracting revolutions to the main drive shaft. The differential is operated by a small motor, which is controlled in terms of cloth skew as observed at the leaving end of the tenter.

With manual control of the motor, the operator must visualize the skew and manipulate the motor switch accordingly. Obviously, this procedure is subject to

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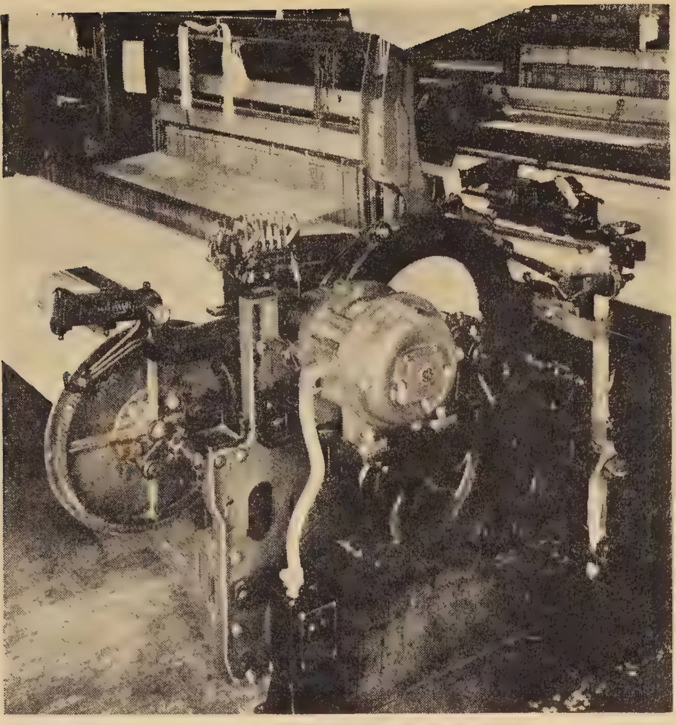


Figure 1. Loom showing cloth in process of being woven

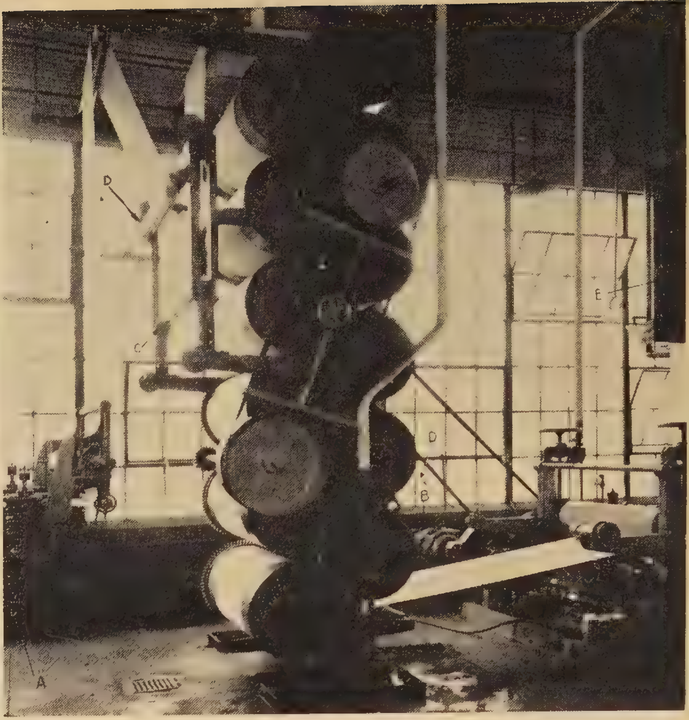


Figure 4. "Dry cans" for drying cloth, with starch mangle at right

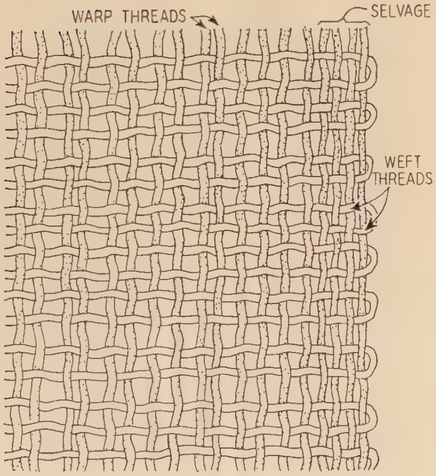


Figure 2. Typical woven material

human limitations and restricted to relatively coarse weaves and low cloth speeds, hence the development of an automatic control became necessary to meet present day standards of finishing with high cloth speeds now employed.

Automatic Control

PRINCIPLES

To automatically control the weft straighteners just described, a method of detecting skew is necessary. Figure 8 illustrates the method of this paper; (*a*) represents weft threads of cloth of one direction of skew; (*b*) cloth having no skew; and (*c*) cloth having the other direction of skew. Outlined on these weft threads are two convergent paths, *A* and *B*, each traversed in the direction indicated by spots of light. In figure 8(*a*), light spot *A* crosses 15 weft threads and spot *B* nine weft threads; in figure 8(*b*) each spot crosses 12 weft threads; and in figure 8(*c*) *A* crosses nine threads and *B* 15 threads. Thus, if weft threads can be made to intercept two spots of light in this manner, a comparison of the rates at which the two spots are intercepted will indicate the direction and magnitude of the angle of skew.

In a practical case, convergent light spot paths can be obtained by moving the two light spots laterally as in figure 8(*d*).

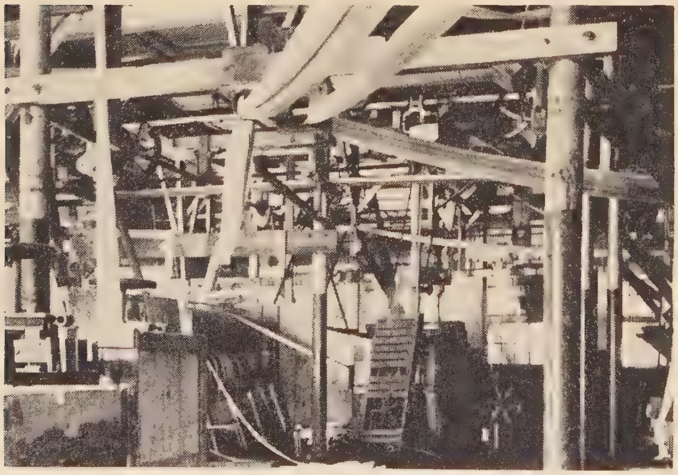


Figure 3. Transportation in rope form through "pot eye" guide

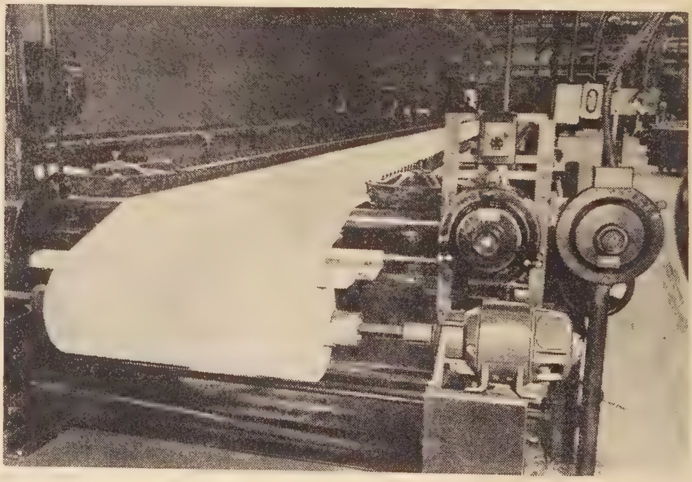


Figure 5. Tenter for restoring cloth to proper width

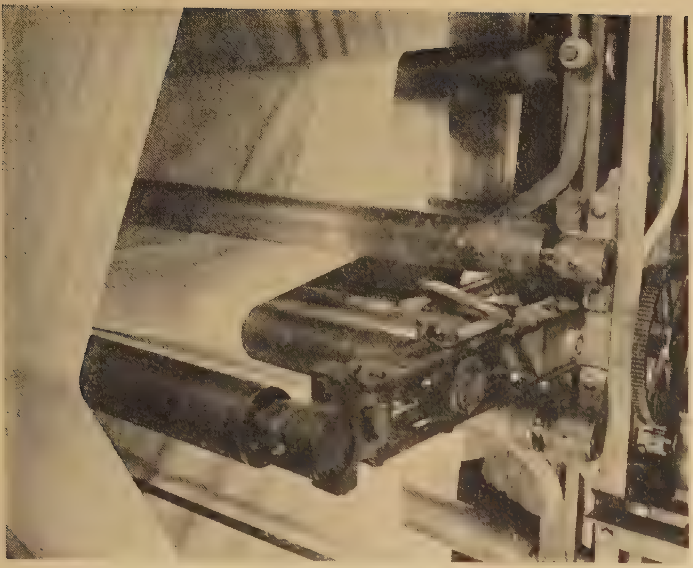


Figure 6A. Canting-roll type of straightener

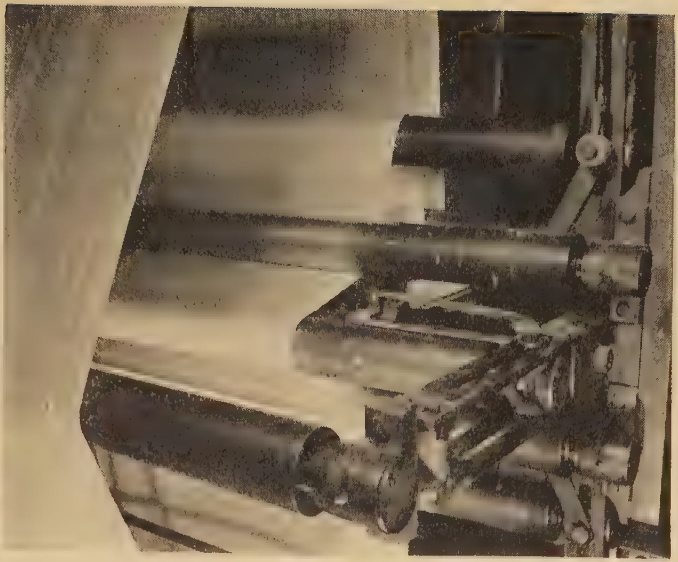


Figure 6B. Canting-roll type of straightener

The cloth moving forward as the spots move inward will produce the required diagonal paths.

To carry out such a principle two things are necessary; first, suitable scanning detectors which will give an impulse for each weft thread interception in the manner just described; and second, a control circuit which will compare the impulse rates from the two scanning detectors and operate the straightener motor when necessary to make the two detectors generate impulses at the same rate.

Scanning Detector Unit

A device for accomplishing the first of these requirements is illustrated in figure 9. A pair of these, one near each edge of the cloth, comprise the complete scanning system of the weft-straightening control.

Each of these scanning units comprises six parts, namely: (1) a scanning optical system; (2) scanning disk; (3) scanning table; (4) detector optical system; (5) amplifier; and (6) a good rigid framework to hold these parts together.

Scanning Optical System

The scanning-unit optical system is shown in figure 10*A* and *B*. The straight filament of the lamp is focused on a slit which in turn is focused on the cloth be means of cylindrical lenses at the end of the optical system housing. The line of light so formed by these lenses is approximately 0.0035 inch by two inches.

The final spot after passing through the scanning disk is 0.0035 inch by 0.063 inch. Its dimensions are determined by the maximum number of threads per inch and their size. Thus it must be thin enough to be completely intercepted by one weft thread. It must be wide enough to span a number of warp threads; otherwise, the warp threads will generate a frequency too. On the other hand, the spot cannot be too wide or at large angles of skew, the weft threads will cross the spot diagonally and not intercept it.

These dimensions are important and are subject to precise calculation for any given set of conditions.

Scanning Disk

The scanning disk is illustrated in figure 11. It is a simple circular duraluminum disk with 16 radial slots $^1/_{16}$ inch wide. The disk is driven at a speed proportional to the cloth speed by means of "Selsyns," the transmitter of which is coupled to the main tenter drive. Thus, the lateral motion of the spot bears a constant relation to the forward motion of the cloth, or in other words, the angle of the path of the light spot is constant.

Scanning Table

Due to the short focal length of the cylindrical lenses, it is necessary that the cloth be held flat at the focus of the light

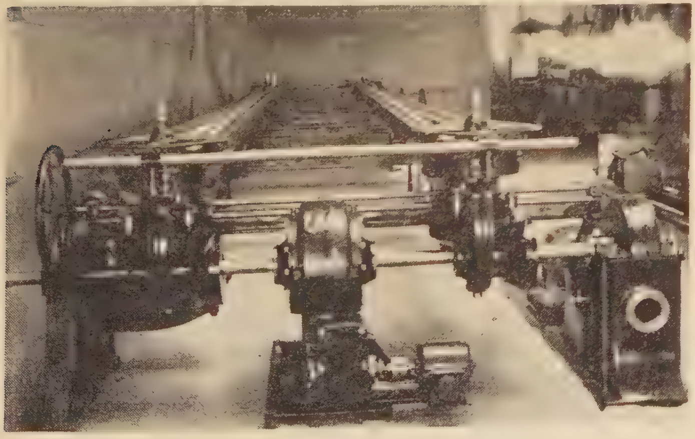


Figure 7. Tenter differential straightener

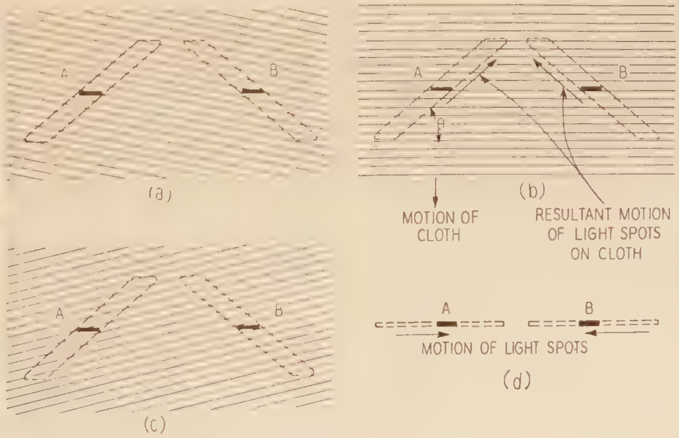


Figure 8. Principles of skew detector

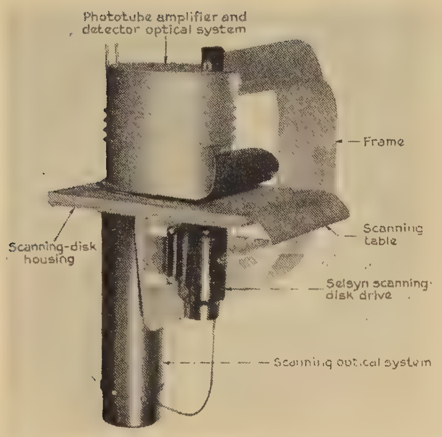

Phototube amplifier and detector optical system
Frame
Scanning table
Scanning-disk housing
Selsyn scanning-disk drive
Scanning optical system

Figure 9. Scanning unit

spot. This is accomplished by passing the cloth over a smooth flat table having a window over the light spot, figure 12. This table is mounted about $^{1}/_{4}$ inch above the normal cloth level so the cloth is drawn smoothly taut across it.

Detector Optical System

After passing through the cloth, the spot of light strikes a large spherical lens in the phototube amplifier housing where it is focused on a phototube, figure 13.

Phototube Amplifier

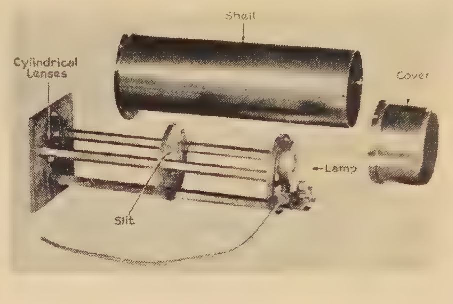
The interruption of the light by the weft threads causes impulses in the output of the phototube. These impulses are amplified by the phototube amplifier before the control transmission unit, figure 14.

The frequency range of the amplifier is from approximately 200 to 12,000 cycles. The gain increases somewhat with frequency to compensate for circuit losses. The primary reason for locating an amplifier in the phototube housing is to change the high-impedance phototube circuit into a low impedance output circuit suitable for transmission to the control unit. Otherwise, an amplifier at this point would have been avoided as excessive vibration is frequently encountered. This vibration has required careful consideration of the amplifier suspension. In the present device, practically complete freedom from vibration has been gained by flexibly hanging from the cover a heavy mass at the center of oscillation of which is suspended the amplifier chassis.

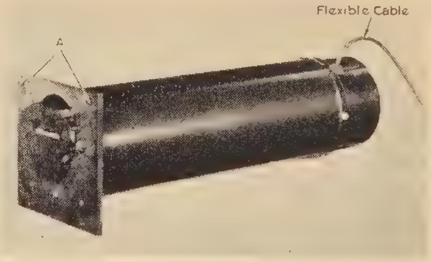
The scanning units are frequently mounted on tenter frames close to drying ovens in which temperatures of 250 degrees Fahrenheit may occur. While the temperature outside is much lower, the phototubes have a maximum allowable temperature of 150 degrees Fahrenheit so in some cases it is necessary to cool the phototube-amplifier housing. This is accomplished by passing cooling water through a few turns of copper tubing soldered to the housing. Very little water is required as the housing should not be cool enough to condense moisture and drip it on the cloth.

Control Unit

The design of the phototube detector and amplifier as described has proved to be subject to engineering calculation. The design of the control unit, on the other hand, has required a considerable amount of experience to insure proper functioning of the equipment. The control unit performs three major functions: first, it compares the impulse frequencies from the two scanning detectors; and second, it operates the straightener motor contactors in the proper direction to correct any skew which may exist; and third, it must so adjust its control of the straightener motor that it will not overshoot in making the necessary correction.



A—Covers removed



B—Assembled

Figure 10. Scanning-unit optical system

The unit which accomplishes this is shown in figure 15*A*, *B*, *C*, and the schematic diagram of the circuits involved is shown in figure 16.

In brief, the operation is as follows: The output of the two scanning detectors is amplified further and passed to the frequency comparator which compares the impulse frequency from detector A with that of detector B. If either frequency is higher, a d-c potential appears on capacitor C_1 of polarity dependent upon which is greater, frequency A or frequency B. The potential, which is a measure of magnitude and direction of skew, then passes through the antiovershoot network and is impressed upon the relay tube which in turn operates relays and they in turn operate small contactors and finally the straightening motor contactor.

Frequency Comparator

Starting with the input amplifier A of figure 16, each impulse produces at the output transformer secondaries a full cycle of alternating current. The initial half cycle of this impulse makes tube A_1 conducting and thereby charges capacitor C_{2A} positive. The second half cycle of the impulse shuts off tube A_1 and makes tube A_2 conducting so that the charge accumulated by C_{2A} is passed to C_1. Thus, each impulse from A first charges C_{2A} positively to approximately one-half the supply voltage and then dumps this charge into C_1 on the next half cycle.

Similarly, the first half cycle of impulse from B charges C_{2B} negatively to approximately one-half the supply voltage and then dumps this charge into C_1 on the next half cycle.

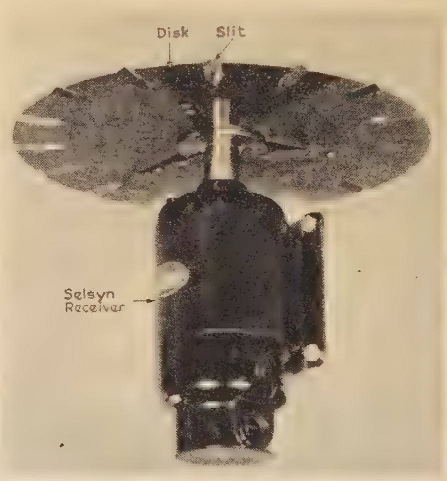


Figure 11. Scanning disk

Thus, if impulses arrive from A faster than from B, C_1 will accumulate a positive charge, and if they arrive faster from B than from A, C_1 will accumulate a negative charge. The charge across C_1 is filtered by resistors R_3 and appears across C_3 as the potential E which is a measure of the magnitude and direction of the skew.

OVERSHOOT PREVENTION

Actual experience in operating automatic weft-straightening controls has shown that care has to be exercised to prevent the correction from overshooting. Consequently, the potential E cannot be used directly on a polarized relay to operate the straightening motor.

The network preceding the relay tube prevents overshoot by doing two things: first, it throws the straightener motor on and off in such a manner as to cause the correcting rate to be somewhat proportional to the amount of skew; second, if there is a considerable skew which decreases suddenly due to the cloth coming through more nearly straight, the network will shut off the straightening motor and hold it off until the skew stops decreasing.

The network is composed of simple resistors and capacitors coupled to contacts on the motor relay contactors.

This action may be explained by the circuit diagram. Under the conditions of figure 16, the straightener motor is not operated. If a skew comes along, C_3 takes on a charge E, which throws one of the grids of the relay tube negative so that its relay drops out and closes the motor contactor. When this happens, the corresponding contact in the anti-overshoot circuit shifts to "in" placing the capacitor C_4 in series with the corresponding grid. This produces no immediate change because the capacitor C_4 has zero voltage. However, as C_4 becomes charged, the negative voltage on the grid decreases until the relay drops out, the straightener motor stops and the contact returns to "out." Capacitor C_4 is now charged and will discharge through R_3 tending to hold the relay-tube grid positive and keep the motor stopped until C_4 is discharged. If there is still a considerable skew, however, the skew control potential E will exceed the effect of the discharging C_4 and the relay will drop out right away and start the motor again. If E is small, a considerable time will elapse before the grid goes negative enough to start the motor. Thus, the circuit starts and stops the straightening motor frequently and the amount of time the motor runs as compared with the amount of off time is a function of the magnitude of the skew. For large angles of skew, the straightening motor will run most of the time and be off but a small part of the time. On the other hand, for small angles of skew, the motor will be off most of the time and will run only a small part of the time.

This explanation covers more or less the static operation of the circuit. In any particular case, the skew-control potential E is likely to be changing continuously. These changes are transmitted through the capacitor C_4 and if sufficiently large will cause the relay circuit to operate on the direction of the change rather than upon the magnitude of the skew. Thus, if E is increasing, the capacitor C_4 will start the motor running more quickly than would have been the case if E had not changed during the sequence of events. Thus, the circuit anticipates to a considerable extent the coming skew condition of the cloth and controls the straightening motor accordingly.

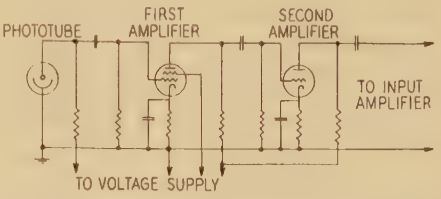


Figure 14. Schematic diagram of phototube amplifier

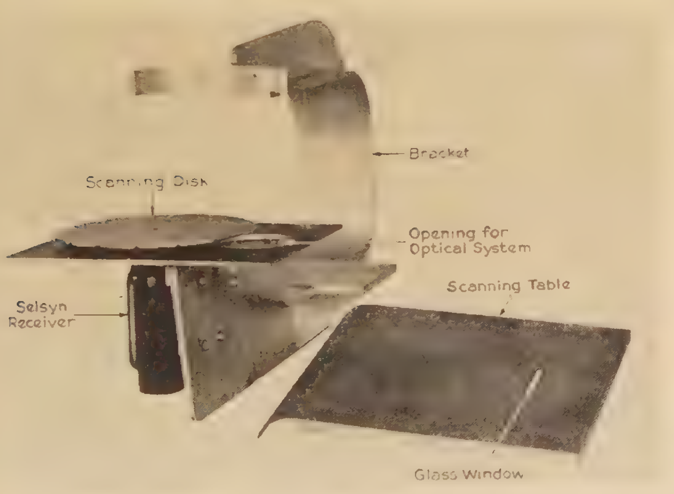


Figure 12. Scanning table with window and main bracket

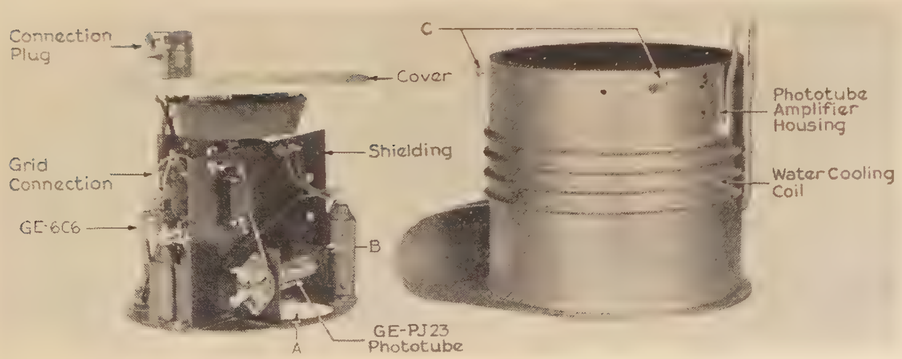


Figure 13 (below). Scanning-unit detector

RELAY CIRCUIT

The relay circuit comprises a twin triode with a relay in each plate circuit. The relays are normally closed and are interlocked so that the motor contactors will be closed only if one of the relays opens and the other remains closed.

CONTROL CONTACTOR CIRCUIT

The relays cannot handle the motor contactors directly so some control contactors are also necessary. These control contactors carry the antiovershoot contacts described above.

SAFETY CIRCUIT

The circuit of figure 16 performs one additional function. In case a large skew-control potential appears, it is probably due to a fault. The cloth may have torn or pulled out of the tenter on one side so that only one detector is functioning or a tube may have failed, the angle of skew may be too great for the detectors to handle, etc. Under these conditions, the safety circuit relay will drop out, opening the motor circuit, light a red lamp or ring a signal, or both.

ASSOCIATED EQUIPMENT

In addition to the scanning and control unit, the other electrical equipment required for automatic weft straightening includes the straightener motor with brake and contactors. These devices must withstand frequent operation and reversals.

Installation

The installation of the equipment is simple, as the complete scanning unit is mounted on one bracket which bolts to the tenter rail, figure 9. The control unit is bolted to a wall or panel by four bolts, figure 15*C*.

Because of the high frequencies transmitted from scanning to control units, the connections between the two pieces of equipment should be as short as possible.

The point at which the scanning units are to be installed is important in some cases. If the cloth under the scanner is completely dry and not pliable, the fact that it is straightened at that point does not mean it will remain straight after it leaves the tenter, because it will tend to return to the condition under which it was dried.

Cloth speed is important because it determines, together with thread count, the maximum frequency of the impulses to be handled. The equipment is now rated at a maximum of 140 yards per minute. At this speed with 80 threads per inch, the thread frequency is 6,720 per second. With a skew of approximately four inches in 40-inch-wide cloth, the frequency one scanner must handle is approximately 12,000 per second.

The maximum frequency to be handled may be further raised by the presence of "bow" in the cloth. Although symmetrical bow affects both scanners similarly and consequently does not cause operation of the straightener, bow may, in special cases push the frequency beyond the range of the amplifier, or it may be of such a sharp angle that the weft threads pass the light spot at such an angle that they do not intercept it. Figure 17 illustrates typical forms of skew and bow.

Cloth Limitations

Most cloth is of the type illustrated in figure 2, although in much of it the number of warp threads per inch may be greater than the number of weft threads. All such cloth, however, has a rectangular texture when held up to the light and practically all of it can be adequately straightened by the weft straightening control. Some cloth, however, is woven to form patterns or the threads may not

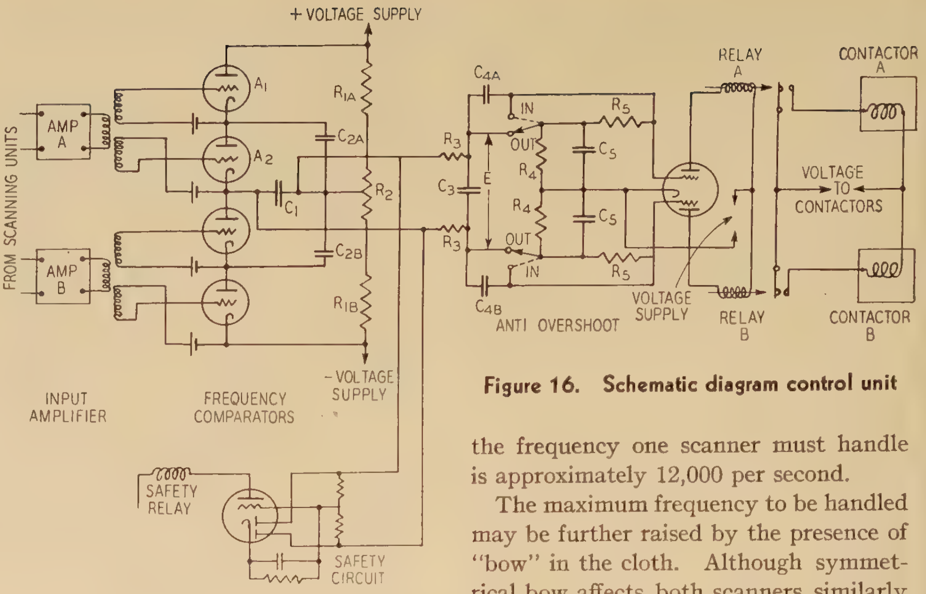


Figure 16. Schematic diagram control unit

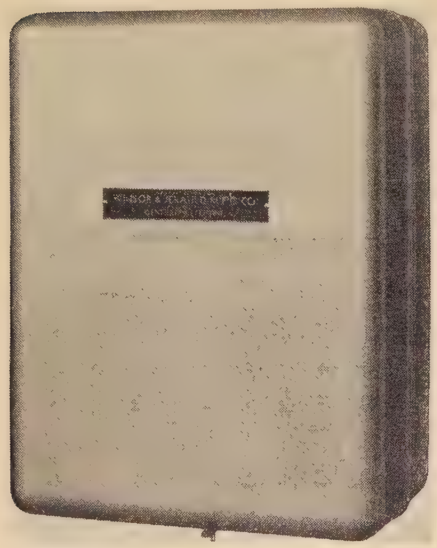
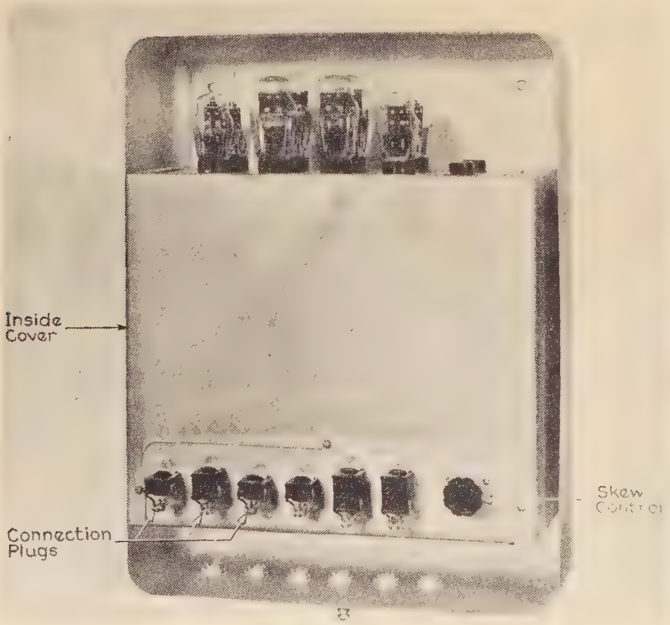
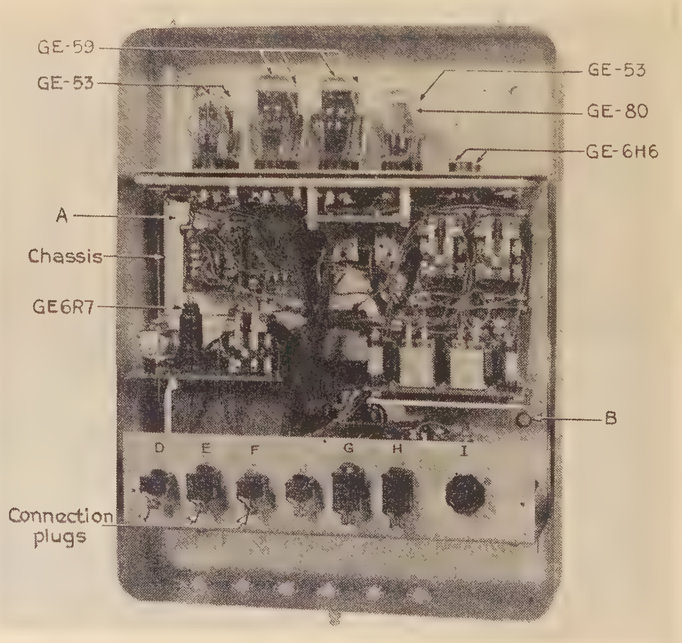


Figure 15. Control unit

A (left)—Completely assembled
B (lower left)—Main cover removed
C (lower right)—Chassis cover removed





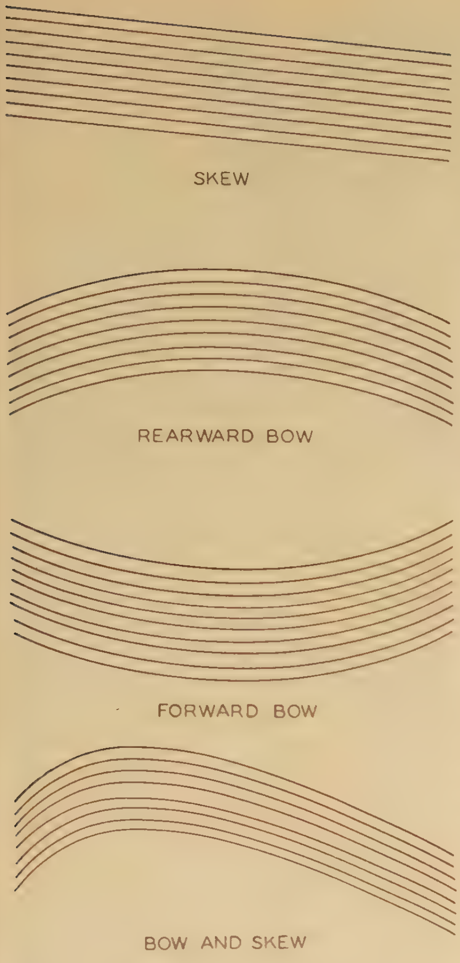


Figure 17. Typical forms of skew and bow

interlace adjacent threads. In such cases, each kind of cloth must be inspected closely to determine whether it can be handled by the automatic scanning unit. In many cases, cloth has actually been straightened which appeared hopeless at first inspection. Loosely woven marquisettes with large tufts have worked very well, even though each tuft blocks off a large part of the optical system.

The optical system was originally designed to handle 100 by 100 thread count which was thought to be about as fine as would be found. Experience now shows, however, that cloth with many more warp threads than weft threads is more difficult to handle than the finest square weaves. For instance, in some types of broadcloth with a weave of 60 by 136, the large number of small warp threads has little or no bending effect upon the relatively large weft threads and consequently the warp threads mat together and in some cases leave practically no interstices.

Another factor decreasing the amount of light is the amount of sizing applied to the cloth. In the cheaper grades of cloth, the interstices appear completely filled. However, the sizing must be at least slightly transparent, because in all cases so far encountered, successful straightening has been accomplished after some experimenting with proper location of the scanning unit.

As might be inferred, a color has no effect upon the operation of the control. The dye is a part of the thread fiber and does not fill the interstices.

Maintenance

In any equipment such as this, the question of maintenance is important. Controls have been in operation over a period of several months without attention and this is to be expected. The equipment contains, however, a number of electronic tubes having a life rating of 1,000 hours although experience has shown this rating to be conservative. The two lamps will ordinarily last several hundred hours, but this will depend to some extent upon the amount of vibration of the particular machine to which they are connected.

The electrical circuit in these controls is necessarily somewhat complicated for ordinary servicing. To facilitate such servicing, the phototube amplifier units and the control units are interchangeable, and in case of failure, a new unit can be substituted in a very few minutes. All connections are made by plugs so changes of units require no wiring.

Application

Several commercial installations of the automatic weft-straightening control have been made in conjunction with the differential-gear-type straightener, typical of which, is that at the Danvers Bleachery, Peabody, Mass. Cotton sheeting after being bleached and washed is finally sized in a twenty-foot tenter where it is automatically straightened, just prior to entering the dry cans. Figure 18 shows the arrangement of the scanning and control units, and figure 19 the complete tenter with dry cans in the background.

Acknowledgments

Any development of this nature is of necessity the result of co-operation of many individuals. The authors wish to acknowledge particularly the contributions of H. A. MacKnight of the Winsor and Jerauld Manufacturing Company who saw the need and participated in the application of the device; also the contributions of T. M. Berry and E. F. Travis of the General Electric Company for many of the essentials that have made the equipment so successful in the field.

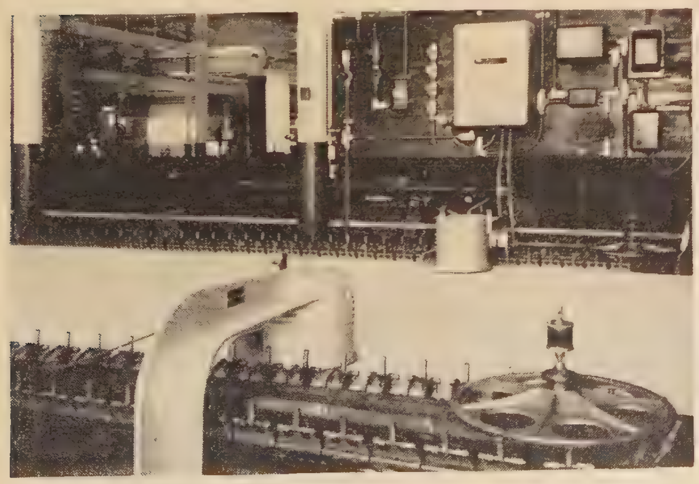


Figure 18. Close-up of Danvers Bleachery installation

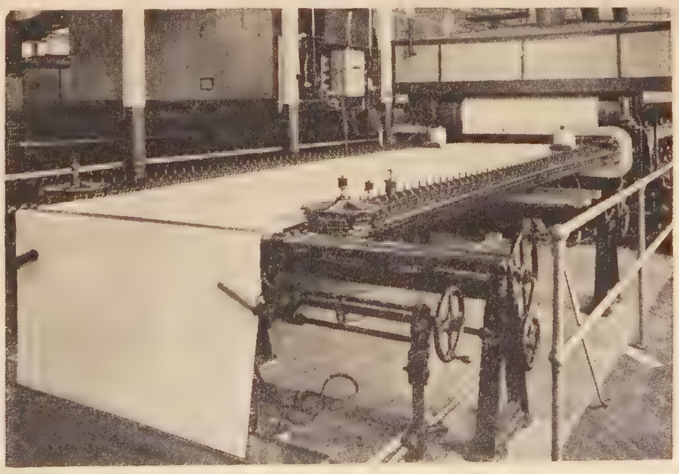


Figure 19. Installation at Danvers Bleachery

Protector-Tube Application and Performance on 132-Kv Transmission Lines—II

By PHILIP SPORN
FELLOW AIEE

I. W. GROSS
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I. Introduction

THE USE of protector tubes (previously referred to as expulsion protective tubes or "deion" gaps) during the past five years or so as devices for protecting transmission lines and equipment against lightning has gained considerable headway, particularly in the protection of high-voltage transmission lines. A number of applications have been made in the medium voltage transmission field, a few in the low-voltage field, and a number of scattered installations for protection of equipment and cables.

Since the protector tube was first proposed[1] as a protective device, considerable experience has been gained in making practical use of this device in the field. The development of any new type of equipment usually consists of a period of experimental work in the laboratory followed by field tests and then more or less limited operating experience before the merits of the device are fully proved. This situation has been true of the protector tube, which is now well past the first two stages of its development. As a matter of fact, the application and operating performance of the protector tube have found quite frequent space in the technical literature during the past few years.[2,3,7,9–13]

The performance of protector tubes on two 132-kv lines was described by the authors in a paper[3] presented two years ago. Since that time three additional 132-kv lines of the interconnected transmission system have been equipped with protector tubes. It is the purpose of this paper to now discuss the tube application to these lines, to give their operating performance, and to summarize the experience which has been obtained on the application and performance of protector tubes on some 250 miles of 132-kv lines equipped with these devices.

II. System Analyzed

The lines on which protector tubes were installed are 132-kv steel-tower lines of the operating companies of the American Gas and Electric Company. These lines are constructed with one ground wire and use standard suspension insulators. The circuits are in vertical configuration. All tower structures are of the double-circuit type. The Roanoke-Fieldale, Fieldale-Danville, and Turner South Point lines are single-circuit. The Glenlyn-Roanoke line is double-circuit, one circuit only being equipped with protector tubes. The Philo-Newcomerstown and Newcomerstown-Canton lines were formerly a continuous line from Philo to Canton, but during the period when equipped with tubes, they have operated as separate line sections, although still located on the same double-circuit tower structures which carry the still-existing Philo-Canton number 1 line. More complete information on the characteristics of the above lines has been presented previously.[4]

In table I is given pertinent information on these lines as regards protector-tube application. It will be noted that the tube-equipped lines comprise 255 miles of line, 1,080 towers, and 3,240 tubes. Dates of tube installation and tube current ratings are also given.

III. Tube Design and Installation Considerations

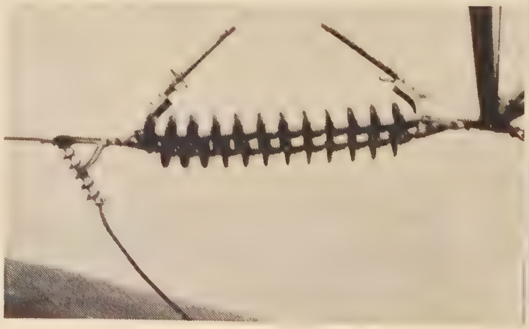
In an earlier paper,[3] what were believed to be the fundamental requirements of protector tubes were presented in some detail. With the added experience gained in the past three years from tube operations, it is still believed that these same requirements are sound; they therefore will not be repeated here. It has developed, however, that certain features of the tubes required still further consideration. Among these are aging characteristics of the tube, installation clearances at points where gas discharges are involved, delayed relay settings of protected circuits to prevent circuit interruption even though the tube has successfully cleared the fault, and changes in the tube design to better its lightning performance and mechanical characteristics.

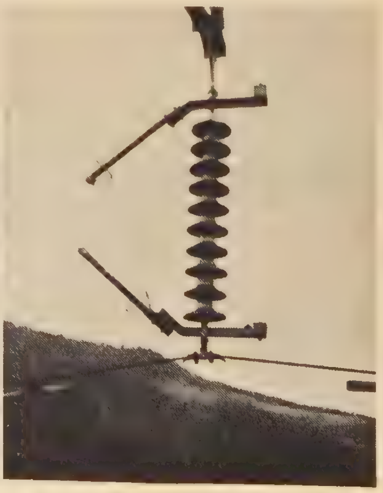
Changes in Tube Design

Some changes in tube design have been made as a result of the experience on the Glenlyn-Roanoke and Roanoke-Fieldale-Danville lines previously reported.[3] Such a change was the result of an attempt to provide a better voltage grading along the surface of the tube. One method of accomplishing this is shown in figure 1 where grading shields have been applied to the tubes. This additional grading was provided on the Roanoke-Fieldale and Fieldale-Danville lines prior to the 1937 lightning season.

Another method used to improve grading along the tube was the use of a resistance material built into the tube itself. This type of construction was used on the more recent tubes installed on the

Figure 1. Roanoke-Fieldale-Danville 132-kv protector tubes with grading shields added in 1937 to improve lightning performance





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1. For all numbered references, see list at end of paper.

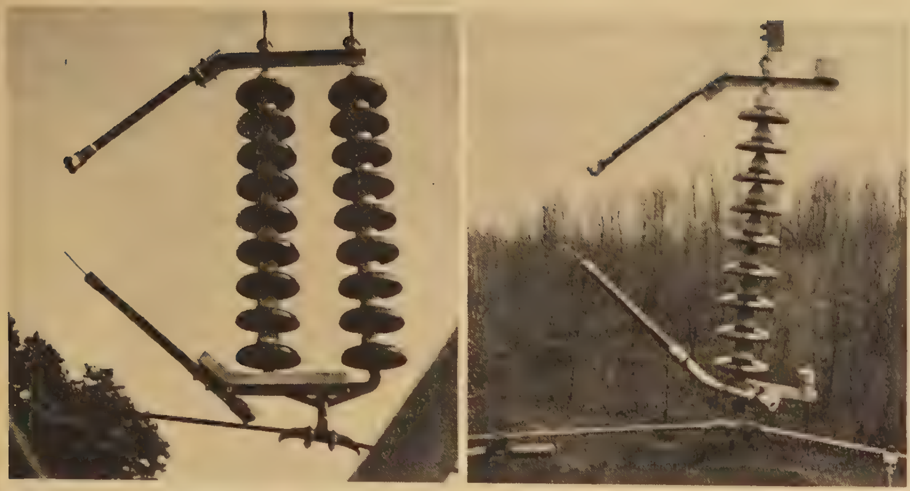

Figure 2. Protector tubes—V type—on Turner-South Point 132-kv line. Note double angle vent at air-gap end of ground tubes, and at bottom end of line tube on single-suspension assembly. Double-suspension assembly has L vent at bottom end of line tube. These types used on Philo-Canton and Turner-South Point lines

Philo-Newcomerstown, Newcomerstown-Canton, Turner-South Point, and most of the new tubes installed on the Glenlyn-Roanoke.

A second change made in the new tubes installed on the Philo-Canton, Newcomerstown-Canton, and Turner-South Point lines is shown in figure 2. This change deals largely with the venting of the gases. It will be noted that gases which formerly vented along the axis of the tube straight into the external gap have now been diverted with a Y fitting at the free end of the tube and so designed as to throw the gases clear of any conductor or grounded structure in the direct path of the discharge. Similarly, venting at the rigid end of the tube has been changed to divert the gases by an L fitting to throw them away from the conductor or other hardware. This change in design has been of a precautionary nature rather than on account of any extensive trouble developed in the initial design.

RELAY SETTINGS

Since the protector tube normally clears a fault in approximately a half cycle, precautions must be taken in the relay setup to insure that high-speed relays do not initiate the tripping circuit during the period when the tube is carrying current. In the tube installations on the Philo-Newcomerstown and Newcomerstown-Canton lines, it was recognized that the relay setup was such that in heavy short circuits near Philo, there was a possibility of the trip circuit being set in action even with normal tube operation. However, to check the limit of low time to which these relays could be set, they were permitted to operate for two seasons with a minimum time of approximately one to $1^1/_2$ cycles. During the last two years, eight relay operations have taken place with perfect tube performance thus indicating that relay time is too short. Three of these occurrences took place in 1936 and five in 1937. However, no service interruptions were experienced. Positive indication that this low time setting of the relay was the cause of the outage was evidenced by the fact that the circuit did not trip at the opposite end.

Results of tests, not reported in detail here, indicate that successful tube operation has occurred even in three cycles. This indicates that a minimum relay time of something in the order of two to three cycles may be desirable on a circuit where tubes are installed. Another alternative may be the retention of one-cycle relaying and the use of ultra rapid reclosing.

PROTECTOR-TUBE CURRENT RATINGS

To successfully interrupt short-circuit currents on the Philo-Canton line protector tubes, it was necessary to develop a tube of higher current rating than previously available. The design work, which was carried on prior to the instal-

Table I. Summary of 132-Kv Protector-Tube Installations

Line Designation	Length (Miles)	Number Towers	Number Tubes	Date Installed	Calculated Fault Amps* Max.	Calculated Fault Amps* Min.	Tube Rating (Amperes*) Max.	Tube Rating (Amperes*) Min.	Vents
Glenlyn-Roanoke	65	270	810	7/ 1/33	1960 3990	660 1250	2500 5000	600 900	Angle†
Roanoke-Fieldale	37	164	492	4/10/34	1960	660	2500	600	Straight
Fieldale-Danville	31	137	411	4/10/34	1350	700	2500	600	Straight
Philo-Newcomerstown	37	140	420	9/ 1/35	9400	1400	10000	1300	Angle
Newcomerstown-Canton	37	164	492	9/ 1/35	5100	1400	7500	1200	Angle
Turner-South Point	48	205	615	4/15/36	3160 5830	1000 1980	5000 7500	900 1200	Angle
Total	255	1080	3240						

† Straight vents prior to 1937. * Root-mean-square.

Table II. Protector Tube Operations,* Glenlyn-Roanoke 132-Kv Line
(Data From Physical Inspection)

	Fiber Tubes				Composite Tubes	
Year	1933	1934	1935	1936	1937	Total
3-phase installations in service	270	270	270	270	270	
Equivalent single-phase installations in service	810	810	810	810	810	
Normal tube operations: Top phase	1	14	10	35	30	90
Middle phase	1	9	6	16	17	49
Bottom phase	1	8	3	14	4	31
Top and middle phases	2	8	1	10	6	27
Top and bottom phases	1	5	3	8	5	22
Middle and bottom phases	0	3	2	6	2	13
Top, middle, and bottom phases	2	8	1	8	7	26
Total tubes	16	87	34	137	98	372
Total towers	9	55	27	97	71	259
Tube flashovers: Top phase	0	5	2	9	2	18
Middle phase	0	4	5	10	0	19
Bottom phase	0	1	0	5	1	7
Top and middle phases	0	0	1	0	0	1
Top and bottom phases	0	0	0	0	0	0
Middle and bottom phases	0	1	0	1	0	2
Top, middle, and bottom phases	0	0	0	1	0	1
Total tubes	0	12	9	29	3	53†
Total towers	0	11	8	26	3	48

* Exclusive of tube target indications due to wind or vibration.
† Including two cases of tube flashover to tower.

Table III. Protector-Tube Operations,* Roanoke-Fieldale 132-Kv Line
(Data From Physical Inspection)

		Composite Tubes			With Shields	
	Year	1934	1935	1936	1937	Total
3-phase installations in service		164	164	164	164	
Equivalent single-phase installations in service		492	492	492	492	
Normal tube operations:	Top phase	12	2	20	15	49
	Middle phase	9	6	11	20	46
	Bottom phase	13	8	15	20	56
	Top and middle phases	5	0	8	7	20
	Top and bottom phases	1	0	2	12	15
	Middle and bottom phases	3	1	8	6	18
	Top, middle, and bottom phases	11	5	14	17	47
Total tubes		85	33	124	156	398
Total towers		54	22	78	97	251
Tube flashovers:	Top phase	0	3	1	2	6
	Middle phase	0	0	3	4	7
	Bottom phase	1	0	2	3	6
	Top and middle phases	0	0	0	0	0
	Top and bottom phases	0	0	0	0	0
	Middle and bottom phases	0	0	0	1	1
	Top, middle, and bottom phases	0	0	0	0	0
Total tubes		1	3	6	11	21
Total towers		1	3	6	10	20

* Exclusive of tube target indications due to wind or vibration.

Table IV. Protector-Tube Operations,* Fieldale-Danville 132-Kv Line
(Data From Physical Inspection)

		Composite Tubes			With Shields	
	Year	1934	1935	1936	1937	Total
3-phase installations in service		137	137	137	137	
Equivalent single-phase installations in service		411	411	411	411	
Normal tube operations:	Top phase	14	0	15	14	43
	Middle phase	8	0	7	15	30
	Bottom phase	8	0	13	8	29
	Top and middle phases	4	0	1	5	10
	Top and bottom phases	3	0	2	3	8
	Middle and bottom phases	7	0	1	4	12
	Top, middle, and bottom phases	4	0	9	8	21
Total tubes		70	0	70	85	225
Total towers		48	0	48	57	153
Tube flashovers:	Top phase	0	0	0	0	0
	Middle phase	0	0	0	0	0
	Bottom phase	0	0	0	0	0
	Top and middle phases	2	0	0	0	2
	Top and bottom phases	0	0	0	0	0
	Middle and bottom phases	0	0	0	0	0
	Top, middle, and bottom phases	0	0	0	0	0
Total tubes		4	0	0	0	4
Total towers		2	0	0	0	2

* Exclusive of tube target indications due to wind or vibration.

lation of tubes for the Turner-South Point and Philo-Newcomerstown-Canton lines, resulted in a tube with a maximum 60-cycle root-mean-square rating of 10,000 amperes. The field test of such a tube successfully discharging 17,800 crest amperes is shown in figure 3. The current record of such a tube discharging is given in the oscillogram of figure 4. Similar tests were reported previously on protector tubes before they were actually installed on the Glenlyn-Roanoke and Roanoke-Fieldale-Danville lines.[2,3]

Types of Tube Installations

The installations previously reported[3] utilized protector tubes mounted on the insulator assemblies with three types of construction. In one, the tubes on the insulator strings were of the so-called V type, in the other, of the parallel type, and in the third, of the 30-degree type but mounted on the structure. In the two more recent installations made on the Turner-South Point and Philo-Canton-Newcomerstown lines, the types of installations have all been of the V type. This procedure was followed due to the fact that the 30-degree type is not particularly desirable from a maintenance point of view as it clutters the tower structure rather badly. Further experience with the parallel and V types had up to that time shown no particular superiority of either, and since the V type was somewhat simpler to install, the decision was made to make the installation on this basis.

IV. Tube Performance

Performance of the tubes themselves under lightning conditions during the time they have been in service up to and including 1937 (excluding Turner-South Point for 1937 only) is given in tables II to VI, inclusive, for the six line sections listed in table I.

Before commenting on the contents of these tables, it should be pointed out that the initial installation of tubes on the Glenlyn-Roanoke line made in 1933 was replaced in 1937 with an improved de-

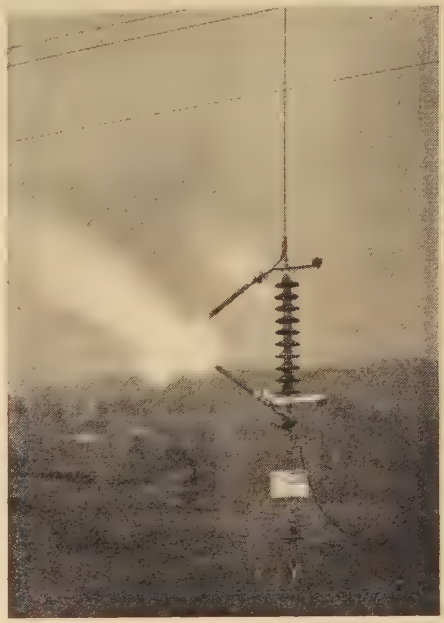

Figure 3. Field test of 1,300/10,000-ampere, 132-kv protector tube discharging satisfactorily 17,800 crest amperes in one-half cycle

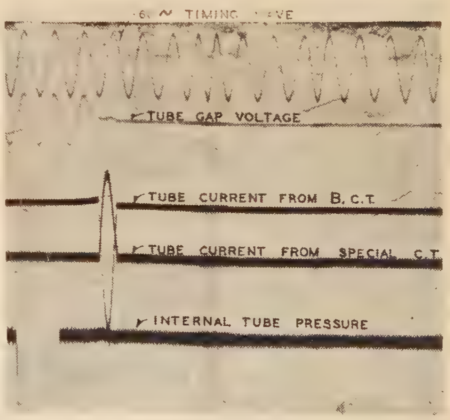

Figure 4. Protector-tube test successfully interrupting 17,150 crest amperes in one-half cycle. This type of tube now in service on Philo-Canton 132-kv line. (Field test November 15–17, 1934—internal tube pressure measured as approximately one ton per square inch)

Table V. Protector-Tube Operations,* Philo-Newcomerstown 132-Kv Line

(Data From Physical Inspection)

		Composite Tubes			
	Year	1935	1936	1937	Total
3-phase installations in service		140	140	140	
Equivalent single-phase installations in service		420	420	420	
Normal tube operations:	Top phase	0	20	17	37
	Middle phase	0	3	9	12
	Bottom phase	0	1	2	3
	Top and middle phases	0	1	4	5
	Top and bottom phases	0	0	2	2
	Middle and bottom phases	0	1	0	1
	Top, middle, and bottom phases	0	2	4	6
Total tubes		0	34	52	86
Total towers		0	28	38	66
Tube flashovers:	Top phase	0	1	0	1
	Middle phase	0	0	0	0
	Bottom phase	0	0	0	0
	Top and middle phases	0	0	0	0
	Top and bottom phases	0	0	0	0
	Middle and bottom phases	0	0	0	0
	Top, middle, and bottom phases	0	0	0	0
Total tubes		0	1	0	1
Total towers		0	1	0	1

* Exclusive of tube target indications due to wind or vibration.

Table VI. Protector-Tube Operations,* Newcomerstown-Canton and Turner-South Point 132-Kv Lines

(Data From Physical Inspection)

		Newcomerstown-Canton, Composite Tubes				Turner-South Point
	Year	1935	1936	1937	Total	1936
3-phase installations in service		164	164	164		205
Equivalent single-phase installations in service		492	492	492		615
Normal tube operations:	Top phase	0	13	22	35	14
	Middle phase	0	8	10	18	6
	Bottom phase	0	1	5	6	6
	Top and middle phases	1	6	3	10	5
	Top and bottom phases	0	2	1	3	2
	Middle and bottom phases	0	2	0	2	0
	Top, middle, and bottom phases	0	2	3	5	4
Total tubes		2	48	54	102	37
Total towers		1	34	44	79	52
Tube flashovers:	Top phase	0	0	0	0	0
	Middle phase	0	0	0	0	0
	Bottom phase	1	0	0	1	0
	Top and middle phases	0	0	0	0	0
	Top and bottom phases	0	0	0	0	0
	Middle and bottom phases	0	0	0	0	0
	Top, middle, and bottom phases	0	0	0	0	0
Total tubes		1	0	0	1	0
Total towers		1	0	0	1	0

* Exclusive of tube target indications due to wind or vibration.

Table VII. Performance of Flashed-Over Protector Tubes

Tube Operation		Glenlyn-Roanoke	Roanoke-Fieldale	Fieldale-Danville	Total
Tubes with one flashover		51	20	4	75
Tubes with two flashovers		1	1	0	2
Tubes with:	one normal operation before flashover	7	4	0	11
	two normal operations before flashover	0	6	0	6
	one normal operation after flashover	5	2	2	9
	two normal operations after flashover	0	0	0	0

sign of tube. The initial tubes were all fiber and had reached the end of their useful life at the end of four years. Since it was found that the fiber, when exposed without protection to the weather, had experienced serious deterioration, the new tube installation on this line, as well as all other tubes now in service on the 132-kv system, have the improved waterproof Textolite covering. In the analysis that follows, therefore, it should be borne in mind that the performance of the Glenlyn-Roanoke line during 1936, when the all-fiber tubes were reaching the end of their useful life, is somewhat worse than would be expected from more modern design tubes even in only reasonably good condition. The data in the tables definitely indicate that tube deterioration on the original tubes had become serious by 1936.

Of the 810 tubes in service on the Glenlyn-Roanoke line during the past five years, there has been a total of 372 successful tube operations, 51 tube flashovers, and 2 tube failures where internal pressure burst the tube (table X). On a percentage basis this gives 87.1 per cent successful tube operations, 12.4 per cent flashovers and 0.5 per cent failures. However, if the high flashover record of 1936, when the all-fiber tubes had badly deteriorated is omitted, the record shows 93 per cent successful operations, 6 per cent flashovers and 0.5 per cent failures.

Of the 492 tubes in operation on the Roanoke-Fieldale line (table III) 398 normal operations occurred during the four-year period. There were 21 tube flashovers and one tube failure. This performance can be stated on a percentage basis as 94.8 per cent successful operations, 5 per cent tube flashovers, and 0.24 per cent tube failures. On the Fieldale-Danville line where 411 tubes were installed 98 per cent of the tube operations were successful and two per cent resulted in tube flashovers. There were no tube failures on this line in four years' operation. As the tube type, rating, age, and method of installation were identical on the two above lines (Roanoke-Fieldale and Fieldale-Danville) the difference in tube performance can be accounted for only on the basis of frequency and severity of lightning conditions encountered.

The record of tube operations on the Philo-Newcomerstown, Newcomerstown-Canton, and Turner-South Point lines (tables V and VI) was much better. For these three lines there have been two flashed-over tubes in addition to 123 successful operations, and two ruptured tubes. This gives 97 per cent successful operations, 1.5 per cent tube flashovers and 1.5 per cent tube failures.

It will be noted in general that a very much better performance is indicated on the Fieldale-Danville, Philo-Newcomerstown, Newcomerstown-Canton, and Turner-South Point lines than was obtained on the initial installation of tubes on the Glenlyn-Roanoke line where the all-fiber tubes were used. It is believed that this better performance is due in part not only to the comparatively short time the tubes have been in service (two to three years) but also to the improvements in design on the newer tubes worked out in the period elapsed between the instal-

Table VIII. 132-Kv Protector Tubes Disrupted in Service (1933 to 1937, Inclusive)

Ref.	Line	Year	Phase	Tube Location	Line Tripout	Remarks
8R	G-R	8/ 8/37	Middle	Line	No	Tube ruptured. Top and bottom phase tubes operated O.K. Tower current 10,300 amperes. Ground-wire current 17,700 amperes.
1R	G-R	6/17/37	Middle	Ground	No	Tube ruptured. Severe lightning. No other tubes operated. No tower current.
113	R-F	9/10/36	Middle	Line	?	Tube ruptured. Top phase tube operated O.K. Bottom phase tube flashed over.
246	N-C	8/21/36	Top	Ground	No	Tube blown off. Fiber threads stripped.
6	P-C	8/25/36	Top	Line	No	End of tube blown off.

Table IX. 132-Kv Protector Tubes Having Repeated Operations (Normal and Flashover)
(Observed by Target Indication)

Number of Tube Operations	Glenlyn-Roanoke		Roanoke-Fieldale		Fieldale-Danville		Total Number	Average Per Cent
	Number	Per Cent	Number	Per Cent	Number	Per Cent		
2	63	12.4	79	16.0	42	10.2	184	12.9
3	13	1.6	14	2.9	2	0.5	29	1.7
4	8	1.0	1	0.2	0	0	9	0.4
5	0	0	0	0	0	0	0	0
Years operation	5		4		4			

lation on the Glenlyn-Roanoke line and these installations.

An analysis of the performance of the flashed-over tubes, made in table VII shows that out of 75 tubes which flashed over, 11 or 13.7 per cent experienced only one normal operation before flashover. Six or eight per cent experienced two normal operations before flashover. Further analysis shows that nine tubes or 12 per cent underwent one normal operation before external flashover had occurred. The above operations are, of course, those noted by target indication and may have actually been somewhat greater due to the possible occurrence of multiple strokes.

Tubes Blown up in Service

When initially applying protective tubes for line protection, the possibility of tube failure due to exceedingly high lightning currents and to 60-cycle currents either above or below the tube rating was considered. As pointed out in table I, the 60-cycle maximum and minimum short-circuit currents of each line were calculated, and tubes selected to cover the range of 60-cycle currents expected. It is gratifying, as will be seen from table VIII, that the record of exploded or blown-up tubes for all lines during the entire time when tubes have been in operation, totals only five, and that of these five tube failures, four resulted in no line tripout, and there is no absolute certainty that a line tripped out even in the fifth case. The experience cited, therefore, seems to indicate that the tubes have been applied within their actual rating, and that the tubes have the ability to safely interrupt 60-cycle currents that can reasonably be demanded of them. Trouble from excessive lightning stroke currents disrupting a tube and producing a line outage appears, from records so far obtained, to be negligible.

Repeated Operation of Tubes

The number of times a tube may be called upon to interrupt currents in service must be considered in estimating the life of the tube. To throw some light on this situation, multiple operations recorded on the tubes from physical inspection of targets in the field have been analyzed and are given in table IX. This record shows that during the five-year period of operation studied here, 184 tubes have operated twice, 29 tubes three times, 9 tubes four times, and none five times or more.

As pointed out under "Multiple Strokes" discussed later, additional duty

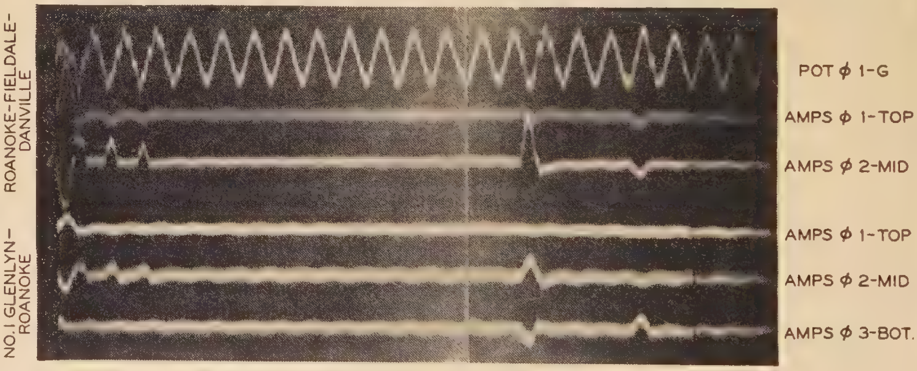

Figure 5. Multiple lightning stroke (five strokes in eighteen cycles) cleared successfully by protector tube. (Oscillogram number 20—June 18, 1937—1:05 p.m.—stroke to Roanoke-Fieldale-Danville 132-kv line.) Note reversal of line polarity at instant of strokes

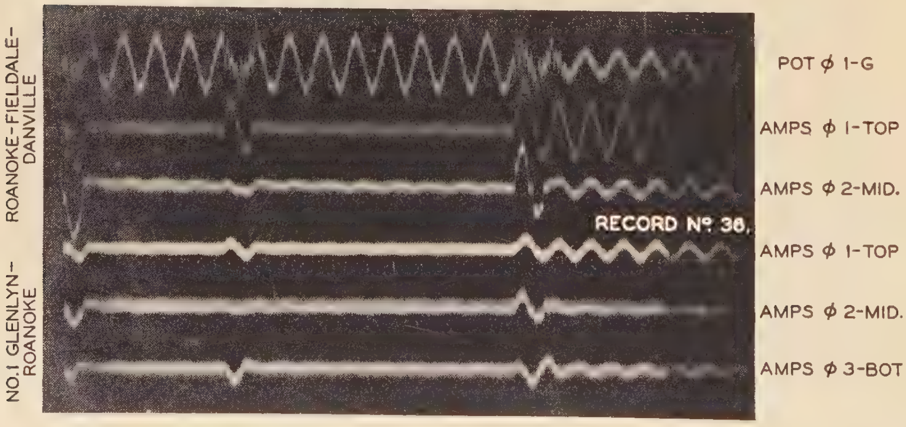

Figure 6. Multiple lightning stroke (three strokes in $13^1/_2$ cycles) which developed into line fault (Oscillogram number 36—July 10, 1937—4:$45^1/_2$ p.m.). Stroke to Roanoke-Fieldale-Danville 132-kv line

Table X. Line Outages Caused by Lightning on Tube-Equipped 132-Kv Lines Before and After Tube Installation

	Glenlyn-Roanoke	Roanoke-Fieldale*	Fieldale-Danville*	Philo-Newcomerstown**	Newcomerstown-Canton**	Turner-South Point
Length of line (miles)	65	37	31	37	37	48
Years in service without tubes	6	7	7	11	11	1
Years in service with tubes	5	4	4	2	2	2
Lightning outages:						
1927	16	9.5	7.9	1	1	—
1928	4	7.6	6.3	3.5	3.5	—
1929	23	12.1	10.1	3	3	—
1930	10	17.5	14.5	1.5	1.5	
1931	22	13.3	11.3	3.5	3.5	—
1932	4	4.5	3.8	1.5	1.5	—
1933	0†	9.7	8.1	2.5	2.5	—
1934	9	1	2	6	6	
1935	5	3	1	7	6	2††
1936	28	7	1	2	1	1¶
1937	4	12	0	1	2	0
Outages per 100 miles of line per year without tubes	20.0	29.0	29.0	8.86	8.56	4.16
With tubes	14.2	15.0	3.2	4.1	4.1	1.04
Ratio: with tubes to no tubes	0.71	0.52	0.11	0.46	0.47	0.25
Ratio: average of six lines	—	—	0.42	—	—	—

* Outages prorated 1927–1933 when part of Roanoke-Roxboro line. ** Outages prorated 1927–1935 when part of Philo-Canton line. † Three outages occurred before tubes were installed July 1, 1933. †† In service seven months. ¶ Tripped at one end only; relays set for three cycles.

Table XI. Lightning Outages on Two-Circuit Lines With and Without Tubes on One Line

Year	Philo-Newcomerstown-Canton			Glenlyn-Roanoke		
	Tube Circuit (Total)	Nontube Circuit (Total)	Both Circuits (Only)	Tube Circuit (Total)	Nontube Circuit (Total)	Both Circuits (Only)
1927	2	3	1	16	13	3
1928	7	7	2	4	5	2
1929	6	7	2	23	17	10
1930	3	4	3	10	6	5
1931	7	6	5	22	23	15
1932	3	4	2	4	4	2
1933*	5	5	4	3†	5	2†
1934	12	21	8	9	8	1
1935**	13	13	6	5	4	2
1936	3	4	0	28	19	8
1937	3	9	0	4	6	0
Tripouts per 100 miles of line per year: without tubes	8.7	10.5	5.0	20.0	17.2	9.4
with tubes	4.1	8.8	0	14.2	13.0	3.4
Ratio: with tubes to no tubes	0.48	0.84	0	0.71	0.76	0.36

* Tubes installed on Glenlyn-Roanoke line July 1, 1933. ** Tubes installed on Philo-Newcomerstown-Canton line September 1, 1935. (One tripout on tube line after this.) † These tripouts occurred before tubes were installed.

is placed on the tube by the multiple stroke. The above data give, however, fairer indications of how many times lightning may be expected to occur at a given location than they indicate how many times a particular tube may be called upon to operate. For example, if a tube is subjected to the effect of four lightning strokes in a five-year interval, and these are multiple strokes each time and the multiple stroke has, say seven successive discharges, the tube would, of course, be subject to 28 discharges during the five-year interval. From the fact that only five tubes have been completely disrupted by internal pressure in the five-year experience cited herein, and four of these tubes failed (perhaps under conditions of direct lightning stroke) it seems quite evident that our experience to date does not indicate that sufficient internal erosion can be expected in the tubes, in four years at least, to become a serious hazard to their life or performance.

V. Line Outage Record

While the performance of the tube itself, that is, its ability to interrupt 60-cycle or lightning currents without damage to itself or without external flashover is important, it must not be forgotten that the ultimate goal of the tube is protection of the line from flashover or tripout. It is therefore of paramount interest to study the record of the tube-equipped lines both before and after the tubes were applied.

The outage record of the six line sections previously referred to is given in table X from 1933 (or date of line installations) to 1937, inclusive. The record of outages on a 100-mile-per-year basis both before tubes were installed and after are given in the lower part of the table. It will be noted that the line outages range from ten per cent to 70 per cent of the outages on the same lines prior to tube installation. Such a comparison, of course, should include an evaluation of the lightning severity and frequency during the period under comparison, two factors which are difficult to evaluate. In general, however, it will be noted that the reduction in outages made averages well over 50 per cent when tubes are used.

While the performance of the protector tube is to prevent line outages, it is also true that when installed on one circuit of a double-circuit line where one circuit only is sufficient to carry the load momentarily during an interruption, the number of double-circuit outages is a major basis on which to judge the tube performance. It will be noted in table XI that in the two-circuit lines involved (Philo-Newcomerstown-Canton and Glenlyn-Roanoke) the two-circuit outages have, for a two-year period, been entirely eliminated on the Philo-Newcomerstown line and have been reduced to 36 per cent on the Glenlyn-Roanoke line. Excluding 1936 when the Glenlyn-Roanoke tubes had deteriorated, the double-circuit outages on this line averaged 1.25 per year for a four-year period or 13.3 per cent of the average double-circuit outages before tubes were installed. Another point of interest in this table is that the outages on the nontube-equipped line in each case have likewise been reduced in the order of 16 to 24 per cent. While the periods analyzed are comparatively short, particularly in the case of the Philo-Newcomerstown-Canton line and it may therefore not be representative of what can be expected over a long period of time, it appears, however, that the tube-equipped line has reduced the number of outages on the nontube line. It is quite reasonable to expect this as well as a reduction in double-circuit outages.

VI. Multiple Strokes

During the time that the protector tubes were in service on the Glenlyn-Roanoke line, an investigation on this line jointly conducted with the General

Electric Company has produced some interesting data on the lightning conditions under which protector gaps are required to operate. A crater-lamp oscillograph[6] was installed at Roanoke for the past four years and many records of the tube performance were obtained thereby. The summarized data on multiple lightning strokes as obtained by the crater-lamp oscillograph in conjunction with protector-gap operations is shown in table XII. It will be noted that successive strokes in one lightning discharge range from two or seven. The polarity of the conductor when line fault is initiated, that is, when lightning presumably strikes, might be expected to be predominantly positive on the basis that some 90 per cent or more of observed lightning strokes to line are of negative polarity. The record in table XII shows that of 300 faults, including single and multistroke faults, in 59 per cent of the cases, the faulty conductor is positive, in 34.5 per cent they are negative, and in 6.5 per cent of the cases, the conductor is near zero potential. Even with the multiple stroke there is no consistency shown in the stroke occurring successively to the conductor or to the conductors which are positive. The conclusion may be drawn therefore although the tendency to be struck is much greater when the line is positive than when it is negative, nevertheless when lightning is ready to strike the line, it often strikes irrespective of the 60-cycle polarity of the line wires.

VII. Conclusions

From the data presented above based on five years of operation in service, and other records and related information too voluminous to present and discuss here, the following conclusions seem justified:

1. Protector tubes, when applied within their rating, appear able to operate without mechanical rupture under all but a few infrequent currents encountered on a transmission system. Even when rupture occurs the faulted line may not and generally will not trip out.

2. Internal tube erosion, as an agent in reducing the current interruption capacity of the tube has not, in five years' operation, appeared as a factor limiting the tube life.

3. The multiple lightning stroke is a factor tending to shorten the tube life of the tube. However, rapidly recurring discharges in a multiple stroke have been successfully interrupted by the tube (three discharges in three cycles have been interrupted satisfactorily).

4. In applying tubes for line protection considerable care should be given to adequate disposal of the discharge gases. Two cases were found where the tubes had apparently flashed to the tower as a result of improper dispositions of gases. Several cases of slightly pitted conductors have also been observed where the gases were expelled directly onto the line conductors.

5. The operation of tube life is still an incompletely solved problem. From a weighing of the present knowledge concerning the theory and performance of tubes it would appear that life depends largely on the weathering qualities of the exterior of the tube covering or surface.

6. The weathering qualities of the tube, and their relation to the tube protective features need further study and investigation. It is suggested that the rate of system recovery voltage may be closely related to this aspect of the problem.

7. Relays on tube-protected lines should either have a definite minimum time to

Table XII. Polarity of Phase Potential at Occurrence of Fault

Multiple Strokes to Roanoke-Danville Circuit

	1934 1935 1936	Total
Record number	40.. 43.. 48.. 49.. 51.. 57..72.. 73 ... 9... 19 .. 40.. 45	
Number of discharges	2.. 2.. 4.. 3.. 2.. 3.. 2.. 7 ... 2... 7 .. 2.. 4	+ ... − ... 0
Phase 1	−+.. 0−..+++.. ++..+−.. ++.. +..0 0 ...− ...+−− −−+..−−..−−−−	
Phase 2	+ ..++.. +..+ + −+..− −......++ + ++.. +−...−++x++ .++ .+−++	
Phase 3	...........................− .. −..+.. + ++ ..−+ + + −− .++ .−+−+	

	1937	Total
Record number	6 9 20 25 36 41 43 44 47 48 59 83 90 92	
Number of discharges	4 4 5 3 3 2 3 3 2 −+ 5 2 4 2 3	
Phase 1	+−−0 − + − −00 −+0 − − + + + −+ + + −+ ++−	25... 26... 7
Phase 2	++ ++?0 −++++ +++ − − + ++ +00 + +−−− −− ++− − +−+	44... 16... 3
Phase 3	+ − + +−− +−+ ++ −++ 0 −+−++ + + +− −+	28... 15... 1

Multiple Strokes to Glenlyn Circuit Number 1

	1936 1937	Total
Record number	10.. 28.. 52.. 54.. 58..74... 31.. 54	
Number of discharges	2.. 3.. 3.. 4.. 2.. 2... 3.. 3	
Phase 1	−−.. 0........0 ++.. +..+.......... −+	5... 3... 2
Phase 2	+..+ −..+−..−0+ ..+−..+............++−	8... 5... 1
Phase 3	........− ..++......................−++..+ 0	5... 2... 1

Single Strokes to Danville Circuit

	1934																			1935								
Record number	1	2	4	7	14	30	31	46	50	53	54	55	56	58	59	60	61	67	79	11	14	19	23	24	25	31	32	34
Phase 1	+	+	+	0	−				+	+	+		+	−	−	+	+	−	+	+	0	+			+			
Phase 2				+	−	+	+	−		+			−	+	−			+		−	+	+	−	+			+	+
Phase 3								+	−	−		+					−				−	−	+		+	+		−

	1936					1937													Total		
Record number	18	20	21	27	33	5	15	16	24	27	28	46	50	63	67	79	89	96			
Phase 1	−	−	+	+	+	+				−	+	−	−	+	+		+	+	22	9	2
Phase 2	+	+	−		+		−	−	−			+				+	−		16	11	
Phase 3	−	−		+			+		+							−	+		9	9	

Single Strokes to Glenlyn Circuit Number 1

	1934												1935		1936		1937			Total		
Record number	3	8	10	12	13	23	27	28	38	44	62	64	12	26	6	37	4	8	19			
Phase 1		+		0		0						+	+			+		+		5		2
Phase 2			−			+		0	+	−	+			−	−	+	+		+	6	4	1
Phase 3	+		+		+		+	−			+					−				5	2	
																				178	102	20

+ Indicates conductor with positive potential when fault begins. − Indicates conductor with negative potential when fault begins. 0 Indicates conductor at zero potential when fault begins. ? Indicates fault with phase indeterminate.

initiate the oil circuit breaker trip circuit of not less than two to three cycles, or as an alternative, when using one cycle relaying, breakers should utilize ultrarapid reclosing.

8. When properly applied the tube protects the line insulators against lightning flashover. No flashovers of insulator strings protected by tubes has so far been observed.

9. Protector tubes have reduced line outages over 50 per cent on the average and show a reduction as high as 89 per cent in the case of one line.

10. Reductions in service outages on two-circuit lines of over 85 per cent have been obtained by equipping only one line with tubes (omitting the one year's experience, 1936—on the Glenlyn-Roanoke line when the initial design tube had become defective).

11. On two-circuit lines, with one line tube-equipped, outages on the nontube line have been reduced by from 15 to 25 per cent.

Acknowledgments

The authors wish to acknowledge the assistance of G. D. Lippert of the American Gas and Electric Service Corporation in compiling and correlating data in the paper, and the co-operation of the staffs of the Appalachian Electric Power Company and The Ohio Power Company in supplying field records of tube operation.

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Discussion

E. J. Allen (General Electric Company, Pittsfield, Mass.): The authors are to be commended for a most comprehensive summary of 132-kv protector-tube operation. The large amount of operating experience accumulated and presented in this paper represents a total of over 10,000 tube-years of service.

Figure 1 of the paper shows the grading shields applied to the protector tubes on both the Roanoke-Fieldale and Fieldale-Danville lines just prior to the 1937 lightning season, as a means of reducing external tube flashovers due to lightning. Table III indicates 11 tube flashovers in the 1937 lightning season, whereas there were 6 in 1936 before the shields were added. It is therefore of interest to analyze this relationship.

Analysis shows that there are two types of protector-tube mountings on these lines; one the V mounting and the other the parallel mounting. These mountings were described in a previous paper[1] by the authors. With grading rings on the parallel-mounted tubes in 1937, no external flashovers occurred except in one questionable instance. Out of 450 parallel-mounted tubes equipped with shields in 1937, 113 normal operations were recorded. Most of the parallel-mounted tubes, or 73.5 per cent, are located on the Fieldale-Danville section, where no external flashovers were reported.

The 11 external flashovers listed in table III for the Roanoke-Fieldale line, however, occurred entirely on the V-mounted tubes. Eighty-two per cent of the V-mounted tubes are located on the Roanoke-Fieldale line, where the external flashovers were reported.

Analysis of reported flashovers shows that 8 out of the 11 external flashovers classified in table III were apparently not external tube flashovers. In all 8 cases where this was believed to have occurred, the single suspension V-mounting, as shown in figure 1, was installed. Targets located on the lower (line end) tubes had operated in every case, and hence the tubes must have discharged internally. The flashover occurring subsequently was probably due to discharge gases from the upper tube improperly contacting the line. The design of tube shown in figure 2 with gas deflector readily overcomes this difficulty. On this basis there would have occurred not more than three external tube flashovers on the Roanoke-Fieldale line in 1937, where grading rings are installed. As table III will show, this is a 50 per cent reduction as compared with the 1936 season, although in 1937 the tubes were called upon to operate 36 per cent more frequently.

The field data on repeated operations and multiple strokes presented in the paper, indicate that the chances of any individual tube having a large number of repeated operations is remote. Except in possibly a limited number of cases where unusually high line exposure to lightning exists, this is in agreement with conclusion 2 of the paper.

Moreover, on lines having an unusually high impulse spark-over level, advantage can be taken of the surplus margin of protection offered by the tube in order to reduce the number of tube operations to a minimum. This is accomplished by increasing the protector tube series gap setting above normal, so that the impulse spark-over is also increased.[2] Care should be taken, however, to allow not less than 20 per cent margin of impulse protection to the line insulation. By this procedure, the lesser magnitude surges would not cause unnecessary tube operations, but at the same time, the protection level of the tube would be adequate to prevent insulator flashovers or outages. For the first few structures out from stations, however, it is probably desirable to retain the normal series gap settings in order to minimize the magnitude of impulse waves entering the station.

As the authors point out, the principal objective of protector tubes is the protection of a line from lightning flashover and resultant line outage. Table X shows protector tubes have reduced line outages over 50 per cent on the average, with a reduction as high as 89 per cent in the case of one line. It is particularly significant that 132-kv protector tubes of modern design installed on one circuit of the Philo-Newcomerstown-Canton line, a distance of 74 miles, double circuit outages have been entirely eliminated over a two-year period. Prior to the installation of protector tubes on the one circuit, this line had an average of 3.66 double circuit outages per year over the preceding nine years.

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1. Expulsion Protective Gaps on 132-Kv Lines, **Philip Sporn** and **I. W. Gross.** Electrical Engineering, January 1935, pages 66–73.

2. Expulsion Protective Gaps, **W. J. Rudge, Jr.** and **E. J. Wade.** Electrical Engineering, May 1937, pages 551–7.

K. B. McEachron (General Electric Company, Pittsfield, Mass.): One might infer from the last sentence of the section entitled "Multiple Strokes" that the polarity of the line might be expected to have some control over which conductor would be struck. There seems to be no good justification for such a point of view. Rather, it is assumed that as a rule the ground wire will be struck, but which tube operates as the tower potential rises is determined to a considerable degree by conductor polarity at that instant.

Table XII shows all of the data plotted with respect to polarity of the protector-tube follow current. Considering the successive discharges of a multiple stroke as a single discharge, follow current occurred 178 times when the conductor involved was positive, 102 times when it was negative, and 20 times when the potential was recorded as zero. The per cent positive, negative, and zero are 59.8, 33.5, and 6.7.

Considering only those discharges which involved but one phase, it is found from table XII of the paper that 50 times the polarity of the follow current was positive and 12 times it was negative. This is shown in table I.

The number of successive discharges as shown in figure 4 vary up to 12 as a maxi-

Table I. Polarity of Follow Currents When One Phase Only Is Involved

Phase Involved	Multiple Strokes Positive	Multiple Strokes Negative	Single Strokes Positive	Single Strokes Negative	Total per Phase
1	9	3	15	2	29
2	10	2	7	4	23
3	4	1	5	0	9
Total	23	6	27	6	

(Column group heading: Polarity of Follow Current for)

mum. Sixteen per cent of all the strokes and 61 per cent of the multiple strokes consisted of at least three discharges, while 4 per cent of all strokes and 15 per cent of the multiple strokes had at least five discharges.

Lewis and Foust[1] have found that of 358 strokes recorded during the years 1934, 1935, and 1936 through tower legs of transmission lines, approximately 95 per cent were negative. Sufficient data are now available both from the present investigation and in the laboratory,[2] so that it is quite certain that the most positive conductor will in general flashover first with a negative impulse applied to the tower or ground wire. This follows since the impulse and the system potential to ground at that instant are additive if the impulse is applied to the tower end of the insulator string.

Perhaps the fact that 95 per cent of the strokes are negative, while but 81 per cent of the follow currents with one phase involved are positive, is partly explained by the possibility of a small but unknown number of strokes to line conductors rather than to the ground wire. From table XII, it is found that phase 1 had 24 positive and 5 negative follow currents when but one phase was involved, phase 2 had 17 positive and 6 negative, while phase 3 had 9 positive and 1 negative follow currents. The top and bottom phases, which are phases 1 and 3, had 83 per cent and 90 per cent positive follow currents, while the corresponding figure for the middle phase was 74 per cent. This might indicate that the middle phase conductor was struck more frequently than the others. However, the data are not sufficiently good to draw such a conclusion definitely.

According to Bewley,[3] the coupling factor between the ground wire and the line conductors would be 0.278, 0.205, and 0.160 for the top, middle, and bottom conductor. On this basis, one would expect the bottom protector gap to operate first, since the coupling is only a little more than half that of the top conductor.

However, the data show that the top conductor (table I of this discussion) had single follow currents involving one phase only 29 times, while the middle and bottom conductors were involved 23 and 9 times, respectively. If it is assumed that negative follow currents mean strokes to the conductor when but one phase is involved, and further assumed that as many strokes occurred to the single conductor when positive as when negative, it might be inferred that the top phase conductor was struck 10 times, the middle conductor 12 times, and the lower conductor 2 times. On this basis, the ground wire was struck 27 times, considering the data of table I. This sort of analysis represents considerable speculation, and is probably pessimistic with respect to the number of times the ground wire was struck.

Another factor which ought to be mentioned is the effect of distance to ground. The ground ends of the insulators on the top phase are approximately 25 feet further from ground than the bottom conductors, which of course acts to increase the potential across the top expulsion protector tube compared with the others, and might be of importance if the applied wave were steep enough.

Number of Conductors Involved

If the number of phases which carry impulse current as a result of protector tube operation is an indication of the amount of current in the stroke, then the data given in table II seem to show that the multiple stroke is likely to contain more current than the single stroke, since of the discharges of the multiple strokes 35.7 per cent involved one phase, while 39.8 per cent involved two phases, and 24.5 per cent all three phases. The corresponding percentages for the single discharges are 52.3 per cent single phase, 37.0 per cent two phases, and 10.7 per cent three phases. Only 3 out of 13 multiple strokes, in which three conductors were involved simultaneously, began with less than three tubes operating at once. This seems to indicate, based on these data, that the first discharge of the multiple stroke is likely to carry current at least equal to or greater than that in the succeeding discharges.

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3. Protection of Transmission Lines Against Lightning—Theory and Calculations, **L. V. Bewley.** *G. E. Review*, April 1937, page 180.

E. J. Wade (General Electric Company, Pittsfield, Mass.): The paper by Messrs. Sporn and Gross is a valuable addition to the field data on the performance of protector tubes. An attempt will be made in the present discussion to show that the data seem to indicate a definite relation between the number of expulsion tube operations and tower ground resistance, and also that the number of tubes which had repeated operations is in close agreement with the number which would be predicted, based on the theory of probability, which allows an estimate to be made regarding the number of discharges through tubes due to multiple strokes.

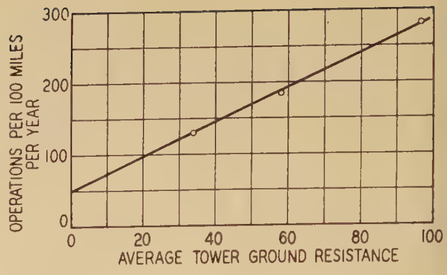

Figure 1. Effect of tower ground resistance on expulsion-tube operations

Examining first the effect of ground resistance, figure 1 of this discussion has been plotted to show the relation between average ground resistance and the number of tube operations per year for the Glenlyn-Roanoke and Roanoke-Danville lines. Since there is a definite difference in the ground resistance of the two halves of the Roanoke-Danville line, the two sections on either side of Fieldale have been considered separately.

As shown on the graph, these data may be well represented by a straight line passing through approximately 50 operations per 100 miles per year at zero tower resistance. If this interpretation is accepted, it means that the difference in the number of tube operations on the two halves of the Roanoke-Danville line is due to variation in ground resistance and not to a difference in lightning severity as suggested in the paper. Where the resistance is higher there is more tendency for adjacent tubes to operate and less stroke current is required to cause operation at the tower which is struck. The point of intersection with the ordinate at zero tower resistance may be an indication of the number of strokes which contact the line conductors. A similar analysis was made with regard to strokes contacting the line conductors and the relation between ground resistance and insulator flashovers in a discussion by S. M. Zubair (Electrical Engineering, volume 55, pages 277–9).

Considering the number of tubes which may be expected to operate more than once, and assuming that any tube on the circuit is equally likely to be struck, regardless of whether or not it has previously operated, then the law of independent trials will apply. This is closely approximated by Poisson's law which may be written:

$P_m(n) = \dfrac{\epsilon^{-mp}(mp)^n}{n!}$ the chance which a given tube has of being hit n times in m trials

p = chance that a particular tube will operate on any one stroke

$= \dfrac{1}{\text{number tubes installed}}$

Table II. Probability Calculations

Line	Number Tubes Installed		Tube Operations One	Two	Three	Four	Period (Years)
Glenlyn-Roanoke	810	Calculated	251	66	11.5	1.5	5
		Field	228	63	13	8	5
Fieldale-Danville	411	Calculated	130	35.5	6.5	0.9	4
		Field	139	42	2	0	4
Roanoke-Fieldale	492	Calculated	178	71	19.2	3.9	4
		Field	215	79	14	1	4

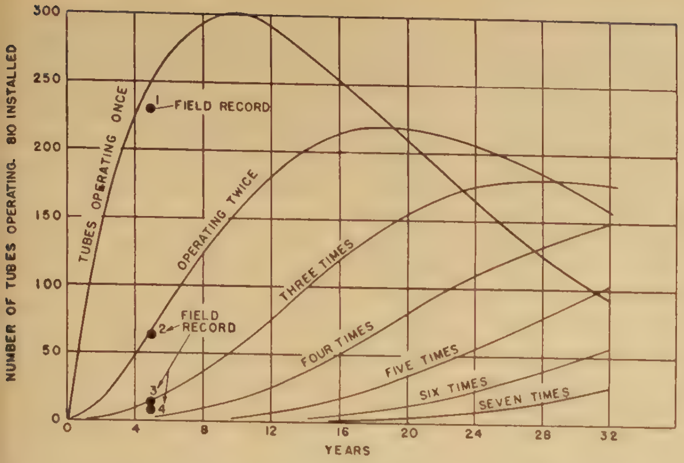

Figure 2. Probability calculation for expulsion tubes operating on Glenlyn-Roanoke line (neglecting multiple strokes)

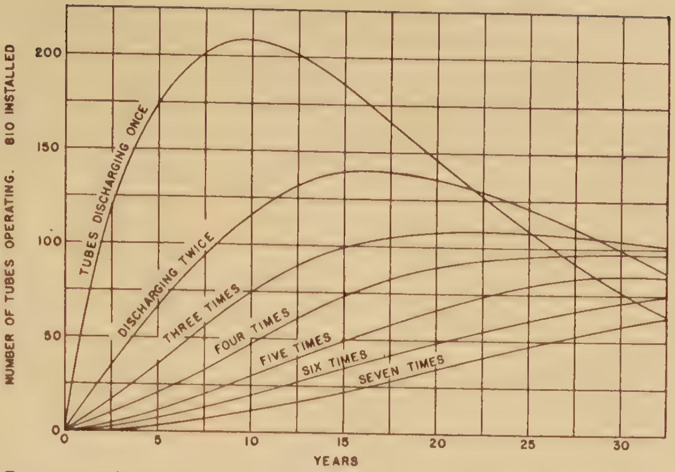

Figure 3. Probability calculation for expulsion tubes operating on Glenlyn-Roanoke line (including multiple strokes)

n = number of times each tube operates

m = total number of operations of tubes for the period being considered

Applying this to the Roanoke lines using the data from tables II, III, and IV of the paper, the results shown in table II of this discussion are obtained. The good agreement which is shown with the field data indicates that tube operations follow rather closely the probability law. The reason for the increasing discrepancy as the number of operations per tube increases is probably due to a few places on the lines which have unusually high exposure. This calculation is shown in figure 2 of this discussion carried out to a period of 32 years. It will be seen that the number of tubes which had six or seven repeated operations is very small even after a long period.

These calculations may be taken as an indication of the number of tubes which would operate on a line passing over level country where the storms are equally distributed. Of course this represents the most optimistic conditions as any line would have some degree of unequal exposure. However, the calculated values check fairly well with the data from the Roanoke lines which are over mountainous territory which indicates that no great discrepancies may be expected.

It is of interest to extend this calculation to include the number of discharges through tubes due to multiple strokes. Mr. McEachron's paper shows that approximately 30 per cent of the strokes over a period of years consist of more than one discharge, 14 per cent of two discharges, 8 per cent of three, 4 per cent of four, 2 per cent of five, and the remaining 2 per cent of six or more.

The probability that a tube will have a certain number of discharges during a given time is the sum of the probabilities of each of the various combinations of single or multiple strokes which can produce the assumed number of discharges.

For instance, three discharges may be obtained by three combinations, namely,

Three "single" strokes,
One "single" and one "double" stroke,
One "triple" stroke.

Similarly, for four discharges there are five combinations, for five discharges seven combinations, etc.

The probability of obtaining each of these combinations is found by taking the product of the probabilities for their components together with the probability of not obtaining any additional discharges.

The results of this calculation are shown by figure 3 and it appears that the chance of an excessive number of tube operations under conditions of equal exposure either due to successive hits or to multiple strokes is very small, since on the average the operations will be rather evenly distributed over the total number of tubes. However, there may be a few cases of tubes having an excessive number of operations due either to multiple strokes or to high ground resistance or to locations of excessive exposure.

As a result of this study, excessive erosion due to a large number of tube operations, is very unlikely except in a very limited number of cases. This agrees with conclusion 2 of the paper.

L. V. Bewley (General Electric Company, Pittsfield, Mass.): The data presented in this paper show that the protector tubes on the top conductors operate more frequently than those on the bottom conductor, in spite of the fact that the line is equipped with a ground wire, and therefore the coupling is materially more for the top than for the bottom conductor, being 0.30 and 0.17 per cent respectively. Such behavior also appears to be typical of insulator flashovers on lines equipped with ground wires.[1] There are possibly four explanations for such behavior:

Inadequate Shielding. By *shielding* is meant ground wires sufficiently high and properly placed so as to intercept the lightning stroke and prevent termination on the line conductors. If the ground wire or wires are not adequate in this respect, a certain percentage of the lightning strokes will evade the ground wires and contact a line conductor. If this occurs, it is the top or middle conductor most likely to be struck. Zubair[2] has plotted flashovers as a function of tower footing resistance, and by extrapolating the curve to zero footing resistance has found the number of flashovers independent of footing resistance. He assigns, as the reason for these flashovers, direct strokes to the line conductors; and arrives at a "shielding efficiency." In the case of the Glenlyn-Roanoke line the shielding efficiency is 0.77, that is 22 per cent of the strokes contacted the line conductor.[1] Of course some of these flashovers independent of footing resistance may have been due to midspan flashover rather than to inadequate shielding.

Tower Gradient. McEachron has suggested in his discussion that tower gradients may overcome the difference in coupling effect and impose flashover on the top conductor. Calculation shows, however, that a rather high gradient would be necessary to accomplish such a result. Let:

E = instantaneous voltage at top of tower and on ground wire

x = vertical distance from top of tower to top conductor

y = vertical distance between top and bottom conductor

C = coupling factor with top conductor

C' = coupling factor with bottom conductor

G = gradient down tower in kilovolts per foot

Then the voltages across the top and bottom insulators are respectively:

$$V = E - Gx - CE = E(1 - C) - Gx \quad (1)$$

$$V' = E - G(x + y) - C'E = E(1 - C') - G(x + y) \quad (2)$$

The difference in voltage is

$$V' - V = E(C - C') - Gy \quad (3)$$

Solving (1) for E and substituting in (3) there results

$$V' - V = (V + Gx)\left(\frac{C - C'}{1 - C}\right) - Gy \quad (4)$$

The gradient necessary to overcome the differential in coupling is that for which $(V' - V) = 0$, and (4) gives

$$G = V\left(\frac{C - C'}{1 - C}\right) \div \left(y - \frac{C - C'}{1 - C}x\right) \quad (5)$$

where V is now the insulator (or protector tube) flashover kilovolts of the top conductor.

For example, consider the Glenlyn-Roanoke line which has a single ground wire and for which the coupling factors are $C = 0.30$ and $C' = 0.17$ for the top and bottom conductors respectively. The vertical distances are $x = 10$ and $y = 26$ feet. The discharge voltage of the protector tube is about $V = 700$ kv. Then by (5)

$$G = 700\left(\frac{0.30 - 0.17}{1.00 - 0.30}\right) \div \left(26 - \frac{0.30 - 0.17}{1.00 - 0.30}10\right) = 5.4 \text{ kv per foot}$$

or a gradient of 5,400 kv per microsecond.

Induced Voltage. When a direct stroke contacts a ground wire it imposes a negative potential on the stricken conductor and, by coupling, on all other neighboring conductors. But the potentials existing on these conductors due to the release of their bound charges by the lightning discharge are positive. This positive potential may or may not be greater on the top than on the bottom conductor, depending upon the heights of the conductors and their coupling factors. In the case of the Glenlyn-Roanoke line the positive voltage is greater on the top conductor by 30 per cent. Now let[4]

$+e$ = voltage on top conductor due to bound charge

$+e'$ = voltage on bottom conductor due to bound charge

Then the voltages across the insulators for the top and bottom conductors respectively are, as in (1) and (2)

$$V = E(1 - C) - Gx + e \qquad (6)$$

$$V' = E(1 - C') - G(x + y) + e' \qquad (7)$$

and the difference in the voltages is

$$V' - V = E(C - C') - Gy - (e - e') \qquad (8)$$

Thus the bound charge voltages tend to neutralize the differential in coupling if, as in this case, $e > e'$.

"Stolen Flashovers." Operating experience has failed to show concrete evidence of midspan flashovers, although calculations indicate that they should occur on many lines. This has lead to the speculation that lightning wave fronts are slower than those used in calculations (one or two microseconds). However, it may be possible, and certainly appears theoretically feasible, that midspan flashovers do occur, but the 60-cycle midspan arc is robbed by a subsequent insulator flashover at the tower.[3] The mechanism of this possibility is envisaged as follows:

Suppose a lightning stroke contacts a ground wire at midspan and flashes over to the (top) line conductor. Then waves of equal voltage move toward the tower. At the tower the voltage on the ground wire is reduced to the *RI* drop of the footing resistance, but the surge on the stricken line conductor is not relieved. The insulator, or protector gap, then flashes over to the tower. But the insulator arc is much shorter than the midspan arc, and the latter therefore extinguishes, leaving the 60-cycle power arc across the insulator. Consequently the "evidence" exonerates the midspan; although the midspan flashover really precipitated the insulator flashover, and an insulator flashover would not necessarily have occurred if one had not taken place at midspan.

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Philip Sporn and **I. W. Gross:** As pointed out by Mr. Allen, of the 11 external flashovers of tubes on the Roanoke-Fieldale line, only three appeared to be what might be called complete tube assembly flashovers, the other eight resulting from expelled gases contacting the line conductor and thus short-circuiting one tube only. This condition was not experienced prior to the installation of the grading shields on the gap end of the V-type tubes. Analysis of tube faults at the time the paper was written had not brought out this point, and we are glad that Mr. Allen has mentioned it in his discussion. It appears that this situation can be taken care of adequately by an alteration in the venting of the tube which certainly would be done in present-day new-tube application.

We believe Mr. McEachron has misinterpreted our statement at the end of the section on "Multiple Strokes," or perhaps the statement was not made entirely clear. What we intended to convey was that since the majority of lightning strokes are negative it might be expected the positive conductor would develop power flashover first regardless of whether the lightning stroke hit the conductor or ground wire. A breakdown of the data in table XII, however, does not indicate that this always is true as there are several cases where the faulted conductor is of negative polarity.

The question of coupling, of course, is distinctly in the picture, and the discussion of Messrs. McEachron and Bewley on this point is an interesting speculation of what may be expected to occur. In breaking down the data of figure 12, however, it does not appear that the faults in every condition can be justified on this basis alone.

The phenomenon of the midspan stroke has always been one which has appeared quite possible in theory but its actual occurrence has heretofore, at any rate not been substantiated by field experience as determined from physical damage to the line. Mr. Bewley's explanation of how this action would take place is most interesting. A large mass of data has been collected during recent years which, if thoroughly analyzed, might throw some further light on this subject.

Regarding Mr. Wade's analysis of the probability of tube operations over a period of time, it is interesting to note how closely his calculations check with field experience. As mentioned in our paper, we do not feel, as a result of our own experience in the field, that erosion of the tube is a factor in determining its life even considering the multiple nature of the lightning stroke.

Corona Voltages of Typical Transformer Insulations Under Oil—II

By F. J. VOGEL
ASSOCIATE AIEE

SOME 13 years ago, Doctor L. Dreyfus[1] published a paper on insulation design of transformers. In this paper, he assumed that electrical breakdown adjacent to square edges was a function of the stress and the distance over which this stress acted; in other words, that it was a function of the voltage gradient along a line of force for some indeterminate distance. By means of conformal representation, he was able to determine the field shape at the corners of structures representative of those in transformers. He could then evaluate the strength of these various structures. His paper was principally mathematical, and it is the purpose of this paper to call attention to his work, to restate some of his assumptions and the conclusions that he reached, and to furnish some experimental data.

In the discussion of the previous paper on this same subject, questions as to fundamental data on the dielectric strength of oil were raised. Data on this subject are included and it is shown that in practical transformer structures, Doctor Dreyfus' assumptions seem to be correct. The relationship is shown that the breakdown of barriers involving the use of square corners theoretically follows the two-thirds power of the barrier thickness. It is also shown that, due to Dr. Dreyfus, quantitative relationships existing between different arrangements can be found and it is thought that they furnish a powerful tool for practical insulation design.

The simplest arrangement of edges is that consisting of two edges opposite each other with various angles of opening α and β as shown in figure 1.

It was found in Doctor Dreyfus' paper, for the assumptions made, that the breakdown strength would vary according to various powers of the distance d. For example, for β equals 180 degrees and α equals 90 degrees (shown in figure 2) the strength should vary as $d^{2/3}$. If β equals 180 degrees and α equals 0 degrees, the strength should vary as $d^{1/2}$. If both equal 180 degrees, the strength was shown to vary directly as d. In addition, Doctor Dreyfus showed that for the case shown in figure 3, the breakdown strength should vary as $d^{2/3}$. The mathematical solution and method of conformal representation can be found by reference to Doctor Dreyfus' paper or a textbook.[5]

Experimental Data for Air and Oil

It is always of interest to check such mathematical calculations with experimental data to see how closely they agree, and to see whether the assumptions are sound. One such check would be to see if the dielectric strength between plane surfaces does vary directly with the distance. In the case of air, data have been published by Schumann,[2] and checks have been made by extrapolating the data for spheres and rounded surfaces in air (figures 4 and 5). These show that the dielectric strength of air between plane surfaces does not vary directly with the distance, but rather as the 0.92 power of the distance.

Cornered electrodes in air have been studied and the results for square-cornered electrodes are shown on figure 6. These results indicate that the dielectric strength for air between a square corner and plane does vary as the two-thirds power of the distance in agreement with the theory.

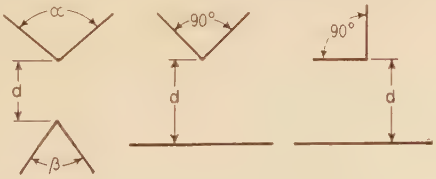
With the above data for air in mind, it is of interest to consider similar data for the dielectric strength of oil. Figure 7 shows data taken on bare rounded electrodes under oil. By extrapolating these curves, it is possible to arrive at the probable dielectric strength of oil between planes as varying as the three-fourths power of the separation, as shown on figure 8. These data were taken in oil at room temperature, and are minimum ten-minute hold values, found by five successive tests at the same voltage. To agree with the theory, the variation should be directly with the distance.

Data for conditions approaching square corners to a plane under oil have been published by Bellaschi,[3] and his results are shown in figure 9. The strength apparently varies about as the one-half power of the separation instead of as the two-thirds power.

The conclusion might now be reached that the assumptions made in Doctor Dreyfus' paper would not hold for oil alone. However, it is to be noted that transformers do not generally use oil alone, but various combinations of oil and insulating materials.

Experimental Data for Insulation Combinations in Oil

In the case of insulation barriers, much data have been previously published. For example, in the previous paper,[4] 60-cycle and impulse data for the $2^3/_8$-inch and $4^3/_8$-inch barriers were published. In these tests, the oil distance from the electrodes to the first or adjacent angle was varied for both thicknesses. It might be expected that the strength of the oil, say for a $^3/_8$-inch space between the electrode and first angle, would be



Figures 1–3. Typical arrangements of electrodes with corners

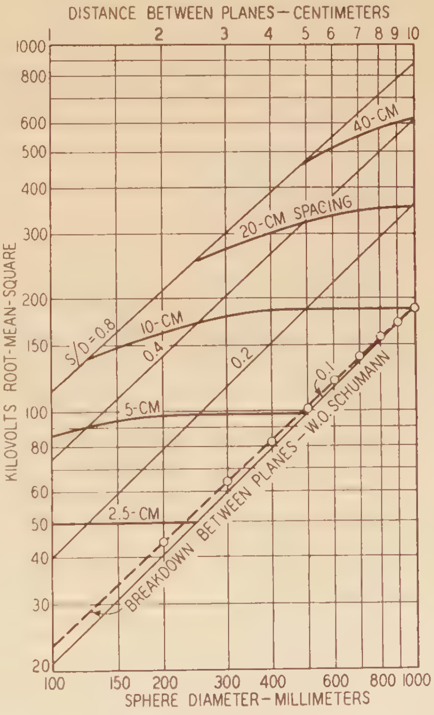


Figure 4. Breakdown voltage in air of sphere gaps with varying diameters at constant spacing

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Paper number 38-52, recommended by the AIEE committee on electrical machinery, and presented at the AIEE North Eastern District meeting, Lenox, Mass., May 18–20, 1938. Manuscript submitted March 14, 1938; made available for preprinting April 19, 1938.

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[1] For all numbered references, see list at end of paper.

constant regardless of the barrier thickness. If so, one of the assumptions in Doctor Dreyfus' theory would be fulfilled, and the corona strength should vary with the two-thirds power of the thickness of the whole barrier; this was found to be the case.[4] It is of interest that the corona strength of the barrier as a whole decreased with increased space between the electrode and the first angle. The following conclusions can be drawn:

1. The dielectric strength of oil depends greatly on the length of the oil space. It is greatly increased in terms of volts-per-inch by decrease in the jump distance.
2. The work of Doctor Dreyfus holds in actual transformer structures and the dielectric strength varies as the two-thirds power of the thickness when the arrangement and allocation of square corners remains the same.

Applications

Once it has been shown that Doctor Dreyfus' assumptions are valid, a very powerful method of analysis becomes possible. Experimental work on barriers can be performed to determine the effect of various arrangements of insulation adjacent to the corner. For example impulse tests were made on a $4^3/_8$-inch thick barrier under oil with seven interleaved angles, and also with only two interleaved angles. Also similar tests were made with the two angles close to the electrode. These barriers were *not* vacuum filled with oil. The impulse strengths of these arrangements were as follows:

Barrier Arrangement	Impulse Strength (Several Shots Only)
Seven angles, equally spaced.........	1,020
Two angles, separated..............	990
Two angles, close together...........	1,200

These tests show the importance of the insulation arrangement adjacent to the corner. The designer can determine the effect of such simple arrangements of various kinds by tests. As described in the previous paper, to obtain maximum and consistent results, it is essential that there be no air included in the assembly.

Once these data are obtained, Doctor Dreyfus has shown in his paper how they may be applied in practical designs. However, his work was mathematical only, and it is easier for a designer to use curves than to work out formulas for each individual case. Curves for some of the simpler cases applicable to practical design are shown in figure 10.

How these data and figures can be used practically for 60-cycle design can be demonstrated as follows:

Let us assume a barrier with an interleaved angle of one-eighth inch thick fullerboard not over three-eighths inch from a square edge. This approximately square edge is to be formed by a copper strap insulated with 0.120-inch thickness of paper. Approximate data for such barriers are shown on figure 11.

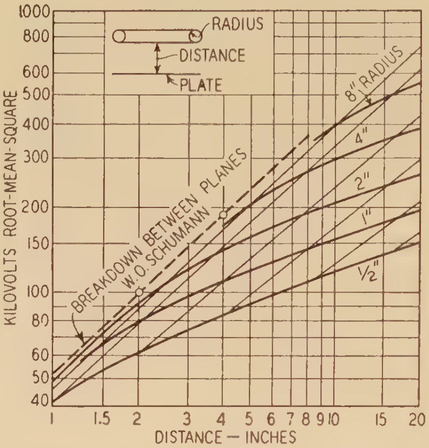

Figure 5. Corona voltage in air between rounded disks and plane, or between rounded surfaces, cylinders, etc., and plane at large separations

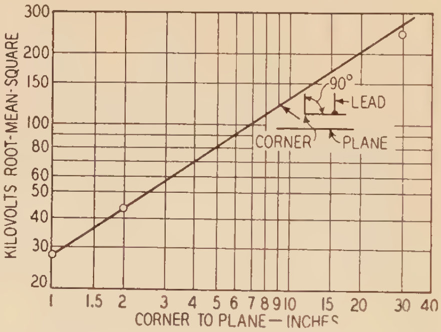

Figure 6. Breakdown voltage in air with square-cornered electrodes

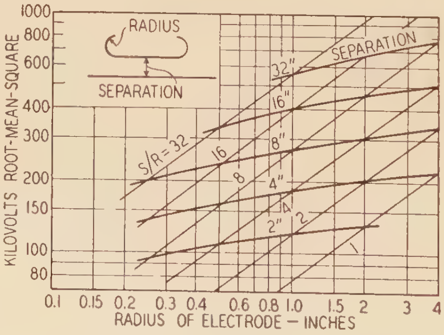

Figure 7. Breakdown voltage in oil between rounded surface and plane, 60 cycles

Heavy curves are for constant separation between surface and plane

Diagonal lines represent constant ratio between separation and radius

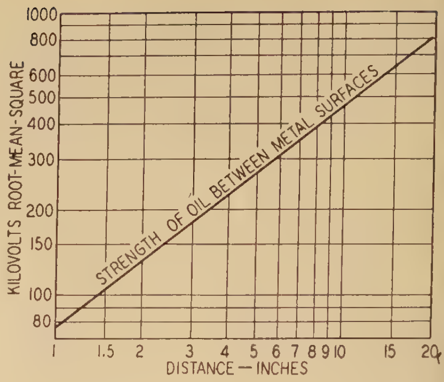

Figure 8. Breakdown voltage in oil between plane surfaces

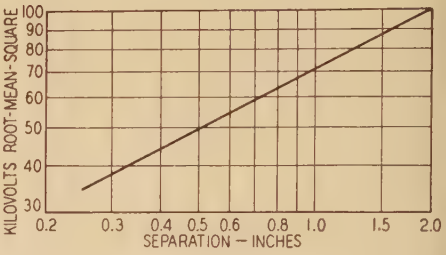

Figure 9. Breakdown voltage in oil with square-cornered electrodes

If we wish to determine safe insulation clearances, for the corner only, for a core type transformer, and for conditions where the space between windings and hence the reactance, is to be kept a minimum, we may refer to figure 10, case I. If we make H equal to about 2 m, it is seen that we can use the fundamental data from figure 11 multiplied by 0.93. It appears useless to make H, the distance to the yoke, much more than three times the space between windings. However, it may be desirable, for shell-type transformers, to keep the space between windings and to the iron the same. To meet 277-kv tests, with *no* factor of safety, a clearance of $2^7/_8$ inches for core type, or 3.6 inches for shell type transformers might be used. These values, of course, should not be used in actual design but are given for illustration of the method only.

Let us suppose that we desire to make a core-type transformer with a thin high-voltage coil as used in some types of series transformers. If the coil were to consist of a single layer, say one-half inch thick, we might apply the data from figure 10, case IV. If we assumed three inches for m, the ratio h/m would be $^1/_6$ or 0.167. From figure 10, the factor is 0.88. From figure 11, a three-inch separation would result in 315 kv

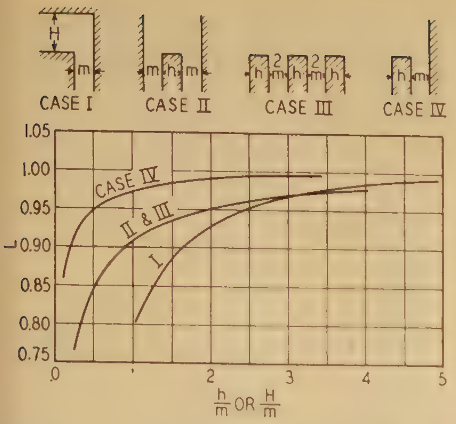

Figure 10. Effect of field form on insulation breakdown in oil of square-cornered electrodes

$V = LV_0$ for cases I, II, and IV
$V = 2LV_0$ for case III
where V_0 equals breakdown in oil between sharp corner and flat plate

strength. Multiplying by the factor 0.88 would give 277 kv strength as in the previous cases.

It is clearly seen that factors for various conditions can be determined either experimentally or mathematically. Thorough tests to determine the dielectric strength on one simple typical corner construction will then furnish very complete information for design purposes. The use of this method is not confined to 60-cycle design alone, since it can be shown that it is equally well applicable to impulse-strength calculations.

Conclusions

The work of Doctor Dreyfus and the tests reported in this paper both show that the arrangement of the insulation at the corners of transformer windings is of great importance to the designer, and that to obtain the greatest strength the area under greatest stress must obviously be free from air. If this condition is obtained, consistent test agreement with the theory for square corners can be obtained, and so-called "form factors" can be developed for design purposes. Experimental data for one reference condition can be derived which will be useful in general applications, and with "form factors" it is unnecessary to make countless other tests for every variation in design proportions.

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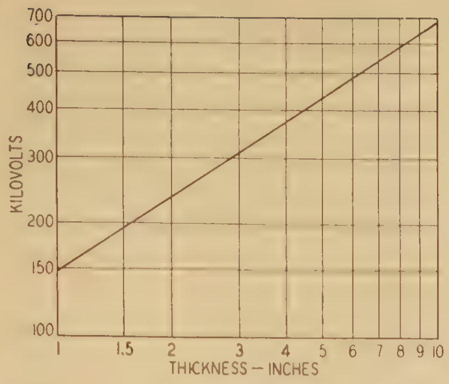

Figure 11. Breakdown and corona voltage in a typical interleaved barrier in oil with insulated electrode

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Discussion

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): Mr. Vogel has presented some valuable fundamental data on the laws of the breakdown voltage versus spacing of air and oil. I shall confine my remarks to the dielectric characteristics of oil, as air is seldom used as an insulating medium in power transformers other than around the outside porcelain of the bushings.

My experience and data have borne out quite well the laws derived by Dreyfus, namely, that for nonuniform fields the breakdown voltage of oil varies approximately as the spacing raised to the $^2/_3$ power, and for uniform fields the breakdown voltage varies approximately as the first power of the distance. My work was independent of Dreyfus' work.

Figure 1 of this discussion shows that with 12-inch vertical disks having one-inch radius on the edges, the breakdown voltage of oil varies as the 0.92 power of the distance. These electrodes produced a fairly uniform field. I am at a loss to know why Mr. Vogel's values shown in his figure 8, giving breakdown in oil between plane surfaces, are so much lower than my values. I note that Mr. Vogel's breakdown voltage varies as the 0.77 power of the distance which does not agree either with Dreyfus' prediction, or with my data (0.92 power).

Figure 1 also shows to what extent the breakdown varies for a given distance with and without pressboard in series with the oil. For example, the highest breakdown is obtained with a thin sheet of pressboard adjacent to each electrode in a vertical position. The lowest breakdown occurs with these electrodes (bare) in a horizontal position. The insertion of $^3/_{16}$-inch pressboard either half-way between the electrodes, or against one electrode only, has very little effect on the breakdown as obtained with oil alone in the gap.

Figure 2 of this discussion shows the effect of the position of the two ten-inch electrodes on the breakdown of oil. These curves show that when the electrodes were horizontal, the breakdown varied as the $^2/_3$ power of the distance. With the electrodes

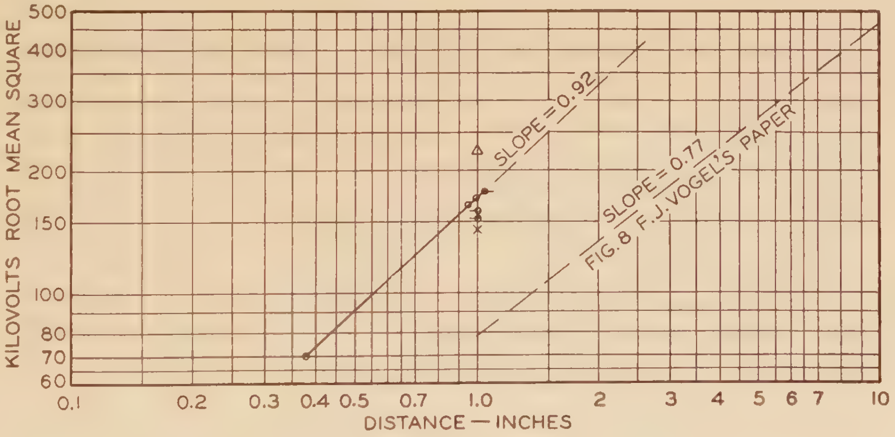

Figure 1. One-minute 60-cycle tests; breakdown voltage of oil between 12-inch disks in vertical position (unless otherwise specified)

Temperature 25 degrees centigrade
One-inch radius—oil strength varied from 28 to 33 kv
(One-inch disks, 0.1-inch gap)

		Spacing (Inches)	Number of Tests Made
△	$^1/_{32}$-inch pressboard + $^{15}/_{16}$ inch oil + $^1/_{32}$-inch pressboard	1	3
o	Oil	$^3/_8$ and 1	14 and 25
o-	$^{13}/_{32}$ inch oil + $^3/_{16}$-inch pressboard + $^{13}/_{32}$ inch oil	1	1
-o	$^3/_{16}$-inch pressboard + $^{13}/_{16}$ inch oil	1	2
x	Oil (electrodes horizontal)	1	12

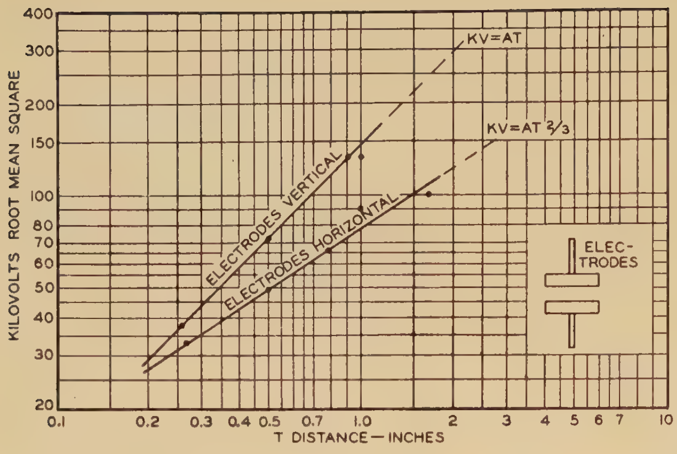

Figure 2. Breakdown voltage of oil between ten-inch disks, 60-cycle one-minute tests

Temperature 25 degrees centigrade

Each point average of five tests

vertical, the breakdown varied directly with the distance. The difference was due, no doubt, to the fact that impurities and gaseous bubbles have a better chance to bridge the gap between horizontal electrodes than between vertical electrodes. Other tests, I believe, have shown that with deaerated pure oil there is no difference in the breakdown between vertical and horizontal electrodes. This is a factor which was not taken into consideration by Dreyfus' work, and it shows that breakdown will not always follow predictions under all conditions.

Figure 3 of this discussion shows the effect of the shape of the electrodes on the breakdown voltage of oil. Briefly these curves show that:

1. The highest breakdown is obtained with large vertical disks having well rounded edges.

2. The lowest breakdown is obtained with a needle point and a plane.

3. With the exception of the upper curve *A*, the breakdown varies very closely with the spacing raised to the $^{2}/_{3}$ power (slope of lines = $^{2}/_{3}$ on log log paper).

Mr. Vogel's figure 11, showing breakdown of a typical interleaved barrier, checks very well my data on breakdown between interleaved windings where the dielectric field concentrates on the edges of the outside coils of each group.

These low breakdown values are typical of a construction having unprotected edges of coils surrounded by oil, which give off corona and break down at much lower voltage than would be required in an approximately uniform field. The importance of protecting electrodes (or windings) against low corona voltage by properly insulating them, was brought out in my AIEE paper on "Co-ordination of Transformers for Steep Front Waves," and presented at last winter's convention. Briefly, with a square edge line end electrode, corona occurred as low as 60 to 65 per cent of the single impulse voltage application strength, while with a proper design of the line end electrode the breakdown point was not only increased but corona did not occur until approximately 80 per cent of the single-shot kilovolt strength was reached.

With ideal electrodes, distances far below those shown in figure 11 are possible. For example, a 138-kv oil-filled cable uses only approximately $^{9}/_{16}$ inch of paper between the cable and lead sheath. In contrast with this, figure 11 of Mr. Vogel's paper shows that in an interleaved design a distance of 2.5 inches will fail at 277 kv which is the test voltage of a 138 kv transformer. In other words, the distance used must be (for a reasonable factor of safety) from six to eight or ten times that used in oil-filled cables. While the minimum distance as used in cables can probably never be obtained in transformers, on account of less ideal electrodes, it is possible with concentric windings to come nearer to the ideal flux distribution than the arrangement shown in figure 11.

From the standpoint of obtaining uniform dielectric fields between windings, the concentric type of winding offers many advantages to the designer, especially in cases where the line connection is brought out from the middle of the stack and the ends of the stack are grounded. There are no sharp corners to be protected and the dielectric field between windings is quite uniform.

With this type of winding even when the line coils are on the ends of the stack, there are never more than four corners where the dielectric field must be improved and these can easily be taken care of by the buffer coils specially designed to keep the stresses below the corona point.

F. J. Vogel: It seems to me that Mr. Montsinger, in his discussion, has lost sight of the principal conclusion. That is, that for similarly shaped square-cornered electrodes, in combination with insulation, the corona point and dielectric strength vary as the dimensions to the $^{2}/_{3}$ power. Even where the edges are rounded slightly, similar laws hold. The use of "form factors" provides the designer with a tool which enables him to vary proportions with security and with a minimum of fundamental experimental testing.

Mr. Montsinger has drawn his conclusions with regard to the breakdown of oil between plane surfaces from data at two relatively small separations, and by average breakdown tests. I think the reason for the discrepancy in values mentioned by Mr. Montsinger is due to the method of test. The tests reported in my paper were the minimum of five ten-minute hold tests instead of average breakdown tests. This explains both the difference in values and in the variation of dielectric strength with distance. It is of interest that for small separations, the breakdown voltage is not greatly affected by the use and location of fullerboard barriers. This is not the case with larger separations or if corona voltage instead of breakdown voltage is taken into consideration.

Figure 3 combines on one sheet data on many different arrangements. They are of interest in not being consistent. Oil, not deaerated, nor carefully processed, varies greatly in dielectric strength. Curve *B* exceeds curve *A* at small separations. They should merge together if the breakdown voltage between planes varies directly as the distance. Either the values from *B* for small separations are too high, or the values from *A* for small separations are too low. The dielectric strength of oil between planes does not vary directly as the distance between them if the latter is true.

Curve *E*, figure 3, is for an electrode condition similar to figure 9 of my paper, and it is noted that Mr. Montsinger's data are lower than mine for small separations and approximately the same for two-inch separation.

In the application of these data to design, it has been found that the corona value

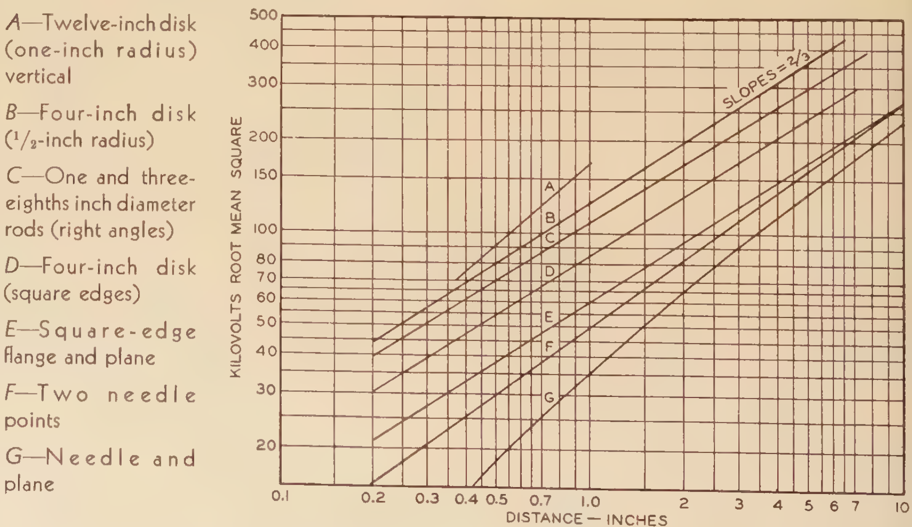

Figure 3. Sixty-cycle breakdown voltage of oil with different electrodes, one-minute tests

Twenty to 25 degrees centigrade
Oil strength ranged from 25 to 30 kv (one-inch electrodes, 0.1-inch gap)

and breakdown value can be made practically equal. At any rate, the ratio between corona voltages, impulse and 60 cycle, can be made the same as the ratio between breakdown voltages, impulse and 60 cycle. It is easily seen that if there is a definite ratio, that voltage values for impulse tests can be established from the present 60-cycle test values and should be consistent. The value of 80 per cent as applied to the ratio between corona and single-shot kilovolt strength is not representative of "proper design."

The comparison of concentric types of winding with interleaved types is unfortunate, since the number of square corners is just the same (four) on the usual core type as in the shell-type winding with two high-voltage groups. However, no merit is seen in the number or lack of number of such corners since one or 20 can be insulated in the same way. Theoretically, some reduction in space between high-voltage and low-voltage windings can be made where the high-voltage lead is brought out at the center of the coil stack, but the outside shield and its insulation required to obtain a satisfactory voltage distribution also takes space and offers difficulties avoided by other types of design.

Systematic Voltage Surveys—Procedure and Application to Distribution Design

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ASSOCIATE AIEE

WITH the development of systems of distribution supplying light, heat, and power from common mains, the problem of maintaining proper voltage at consumers' services has become extremely difficult. The efforts of distribution engineers in solving system voltage regulation problems have extended in many directions. To facilitate these solutions, a need has been felt by many distribution engineers for some means of clarifying the approach to the voltage-regulation problem. The systematic voltage survey, by presenting a comprehensive view of service voltage conditions, has been found, by utilities which make such surveys periodically, to serve this purpose effectively. This paper presents a procedure for conducting systematic voltage surveys, based on the practice of various electric utilities, and a brief discussion of the application of voltage-survey data.

Distribution systems are not static, but are in a continual process of development. In the course of rearrangements occasioned by load growth, some primary and secondary mains become too long, or overloaded, or distribution transformers become overloaded, with resultant adverse effect on regulation standards. To maintain voltage within system regulation standards under these conditions, the distribution engineer must have some method of ascertaining the status of service voltage conditions over the entire system. Because of the variable factors involved, it is impractical, if not impossible, to calculate with any degree of accuracy the value of voltage at consumers' services, involving as this may, approximations of load on primary laterals, distribution transformers, secondaries, and services. The systematic voltage survey is an effective means of obtaining this information, and has proved to be a material aid to the distribution engineer in providing good voltage service.

The procedure involved in making a voltage survey necessarily varies among different utility systems in accordance with individual system requirements. Data received from various companies regarding voltage survey practice indicate, however, that there is considerable uniformity in the consideration of certain fundamental aspects.

In considering plans for making a voltage survey for the first time, engineers are concerned with certain phases which may be divided into the following categories, namely,

(*a*) Preliminary engineering considerations.
(*b*) Preparation of data for field test forces.
(*c*) Procedure for field testers.
(*d*) Recording of tests, classification and tabulation of results.
(*e*) Analysis and application of data.

Preliminary Engineering Considerations

The value of a voltage survey is primarily dependent on the relative accuracy and the completeness with which the information obtained presents an indication of the true status of voltage conditions on the system. To insure the effectiveness of the survey from the standpoint of the final engineering use to be made of the data obtained, careful consideration must be given to the type of readings desired, location and number of readings to be taken, time of taking readings, etc.

TYPES OF READINGS

There are two basically different types of voltage surveys—those taken by means of graphic instruments, and those taken by means of indicating instruments. Although the cost of a voltage survey is on the whole increased by the use of graphic instruments, the added cost is offset by the fact that a complete record of voltage variations and fluctuations over a 24-hour period is available, which in many cases adds greatly to the understanding of the regulation problem. On the other hand, the use of indicating instruments speeds up a voltage survey and allows the use of a less highly trained personnel. The element of completeness is taken care of by increasing the number of readings taken. In this connection it may develop that a large number of indicating readings thoroughly covering an area will prove of greater value than a limited number of graphic records taken at a few points only, as the few graphic records may fail to disclose the extent of the poor voltage conditions. As a rule, a large number of indicating readings taken in an area should not fail to disclose low spots and high spots; and where conditions are suspicious, they may be supplemented by the more thorough graphic charts. This is usually the practice of companies which standardize on indicating readings.

The use of graphic instruments permits a check on the average voltage supplied to a consumer, which is important as it is desirable that the average voltage supplied by a system shall match the rated voltage of equipment for best service to the consumer. Nevertheless, most systems have set up *limits* of voltage service and their experience has been that if the greater part of the service voltages are kept within these limits, as indicated by spot readings, the average voltage supplied to the services will not deviate greatly from the system nominal voltage.

LOCATION AND NUMBER OF READINGS

In arranging the details of survey procedure, a most important point to be de-

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cided is the location at which readings should be taken. The voltage which influences the operation of equipment is that which is directly supplied to the terminals of the equipment; however, it is not practical, for example, to measure the voltage at the lamp sockets. The next best point, therefore, is considered to be at the consumer's service switch.

Practical considerations preclude taking voltage readings at all services. The number of readings taken should be sufficient, however, to represent a fair sampling in order that the results may be indicative of the conditions existing. To facilitate subsequent corrective measures, readings should be taken at a sufficient number of service points to disclose whether subnormal voltages are caused by primary circuits, secondary mains, or services. On radial systems readings should be taken at the consumer nearest each transformer and at a consumer at the end of at least the longest secondary branch. Where a secondary has several branches of unequal loading or a complicated configuration, judgment may dictate that more than one branch reading be taken. Special conditions may warrant taking additional readings at various points along the secondary.

A careful analysis of secondary layouts, in establishing a voltage-survey procedure, will do much to eliminate unnecessary readings. Where considerable growth is taking place on a secondary system, a certain amount of secondary rearrangement is made from year to year and successive voltage surveys must be made to conform. On the other hand, it has been found good policy in making successive surveys to choose locations in a consistent manner, and where no rearrangement has been made, to choose approximately the same locations as before in order that yearly comparisons of results may be more closely indicative of actual change.

On network systems many of the same points hold. As network secondary grids are fairly uniform in arrangement, a reading at the first consumer off the transformer and at one or two intermediate points between transformers generally suffices. Where the network grid is incomplete, additional readings on long spurs may be desirable.

NUMBER OF READINGS AT INDIVIDUAL LOCATIONS

The decision must be made as to whether or not all possible line-to-neutral readings should be taken at each location. Practice naturally differs, but with indicating instruments, particularly, the additional time and expense involved in taking more than a single line-to-neutral voltage would appear to be justified by the information obtained regarding voltage unbalance. For this reason, where a choice of consumer locations is available, three-wire services are to be preferred to two-wire services. In the case of three-phase secondaries the readings should be taken, wherever possible, on a three-phase service. It may be desirable to read the line-to-line voltages as well as the line-to-neutral values—the former for reference and check purposes, the latter for comparative records.

TIME AT WHICH READINGS ARE TAKEN

In a district which is predominantly residential, the peak load will usually occur at some hour during the evening in the winter. If a district is on the average an industrial district, the peak load will usually occur at some hour during the day and may be either in the summer or in the winter. There may be some residential load in an industrial district and some industrial or commercial load in a residential district, but if these loads make up only a small portion of the entire area, the expense of surveying them separately may not be justifiable. In general, the readings should be taken at the time the peak load is occurring in the district.

The time of the year and the extent of time over which the survey will be conducted will be determined ordinarily by the load characteristics of the system and the personnel available for carrying on the field work. Common practice is to schedule the ordinary lighting-load survey over the winter months and the survey on industrial loads and summer resorts over the summer period. This allows a year-round distribution of work on the field test forces. It has been found convenient by some systems to schedule daytime industrial-load readings as well as night lighting-load readings over the "winter peak" period to fit in better with the routine work of the field forces and relieve special personnel requirements.

Where seasonal variation of load over the "winter peak" period is limited, it may be feasible to schedule the voltage survey for any time during the period from October to April. If the load variation is considerable, it still may be desirable to take readings over a long period and correct voltage readings for variation of system demand. Such voltage readings can be corrected to allow for the difference between the feeder load at the time the readings were taken and at the time of feeder peak.

Generally speaking, readings in residential areas will be taken on week-day nights from 6:00 to 10:00 p.m. It may be desirable to take readings in store-load districts on Saturday nights. In industrial districts readings may be taken between 9:00 a.m. and 4:30 p.m. with allowance for the noon-day load dip. Where there is any doubt, an analysis of feeder load characteristics will indicate the desirable time for a particular area. Corrections for "off time" readings are not generally made, unless they are found on the "border line."

Preparation of Data for Field Test Forces

With the question of type of data decided, thought must next be given to the procedure for obtaining the data.

Prior to the beginning of field operations a certain amount of engineering study will generally be found necessary. The territory should be divided into the districts by which it is desired to keep records. Whether the territory consists of a closely built up urban area or an extended system with natural divisions, it will usually be found advantageous to proceed with the survey in terms of such districts as best fit the system, such as by towns, substation districts, or arbitrary divisions used in connection with existing operating records. For convenience it may prove advantageous to subdivide the major divisions to correspond to the grouping of secondary circuit maps. Tabulation of the readings by districts, adopted on this basis, will facilitate the analysis of voltage conditions and help in the consideration of plans for system reinforcements. Further tabulations can be made according to types of load, for example, residential-commercial and industrial readings.

Some form of indication must be devised to indicate to the field forces where and when readings are to be taken. This can be done by using secondary maps as the direct medium of designating the locations at which readings are to be taken, as illustrated in figure 1. These secondary plates are designated by plate numbers to which the survey records are indexed.

A procedure for using these plates in connection with indicating readings is as follows: A volume, consisting perhaps of approximately 100 blueprint plates covering a district, can be inspected by one or more engineers familiar with the secondary system to determine the lo-

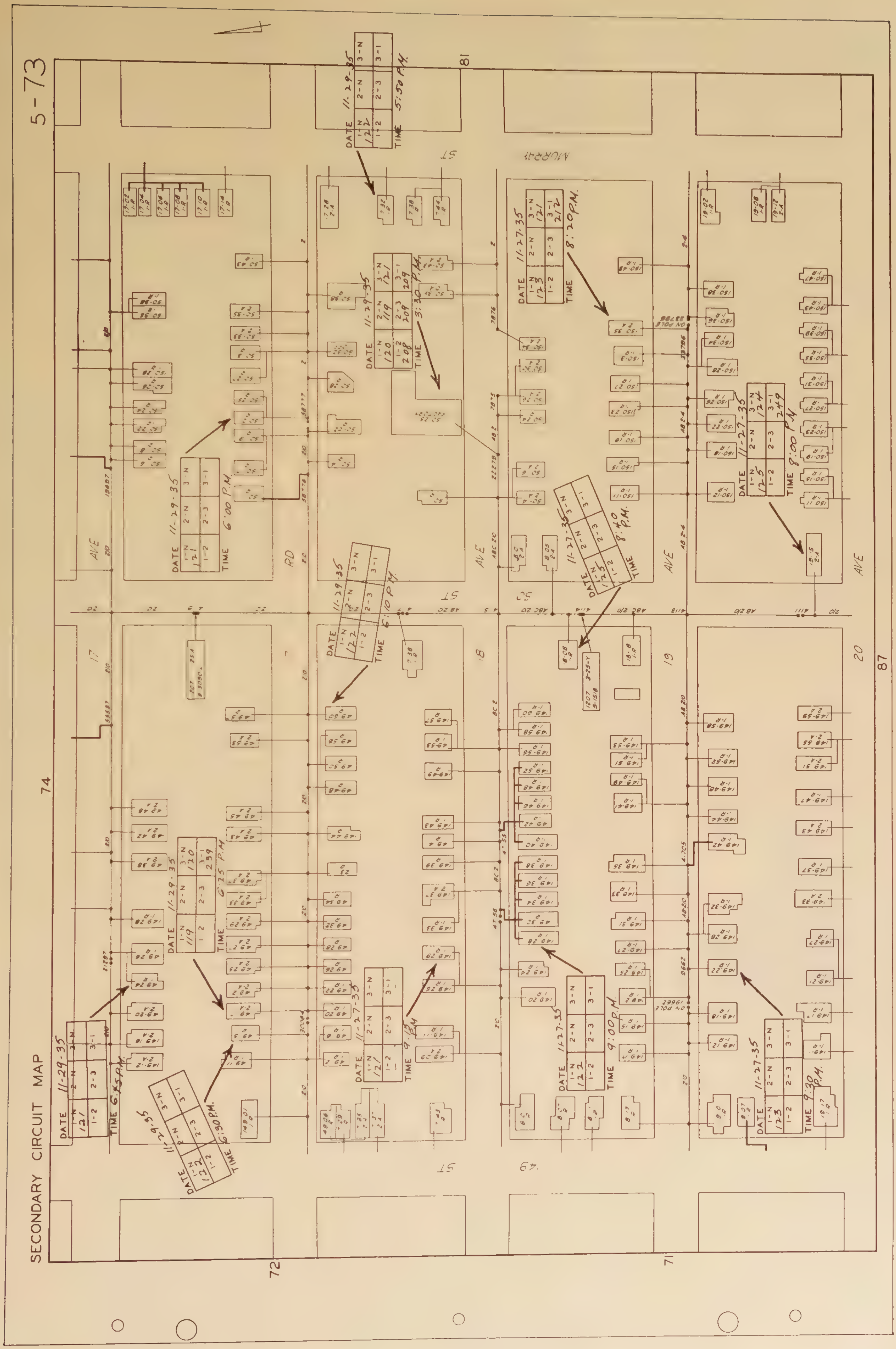


Figure 1. Secondary-circuit maps adapted for voltage-survey use. Test locations shown and indicating readings recorded directly on secondary blueprints

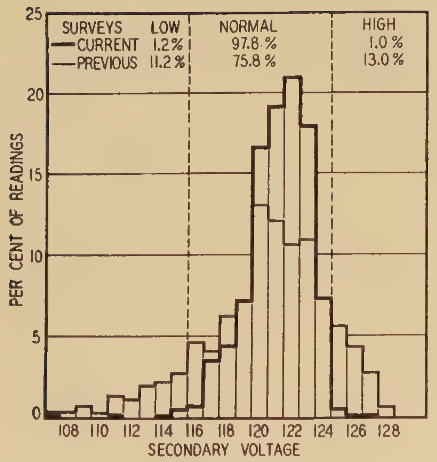


Figure 2a. A-c radial-system voltage survey, Verona district. Night readings

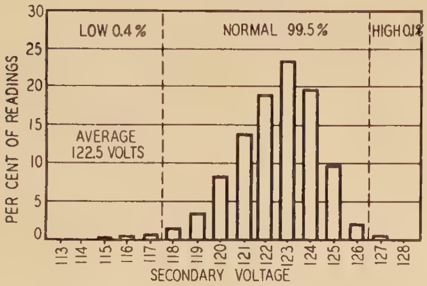


Figure 2b. A-c network-system voltage survey Night readings. Summary of all districts

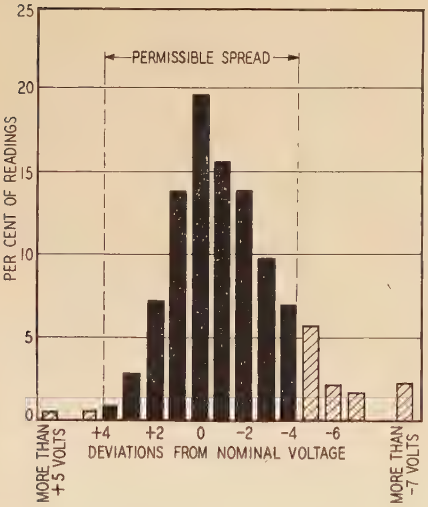


Figure 2c. Service entrance voltages during principal lighting hours, district A

cations at which readings should be taken. These locations can be indicated by arrows on the secondary plates as shown in figure 1, using a color code for the arrows, for example, as follows:

Network System

Night readings (lighting load)—yellow
Day readings (industrial load)—green

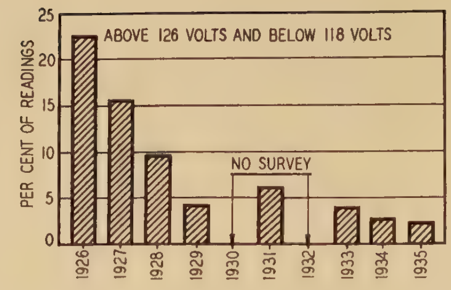


Figure 3. A-c radial-system voltage survey Readings outside normal range Summary of all districts

Figures 2 (left) and 3 (above). Typical charts summarizing service voltage conditions on the distribution system as disclosed by the voltage survey

Radial System

Night readings (lighting load)—red
Day readings (industrial load)—white

The differentiation by colors between network and radial systems will aid in the final classification of readings for tabulation purposes. The field forces are interested only in the distinction between day and night readings.

After a volume has been "marked up" for locations, box forms should be stamped on the blueprints, using contrasting indelible ink, adjacent to the arrows, as shown in figure 1. The box forms should be large enough to contain the readings recorded by the testers. After a sufficient area has been covered, the marked up plates should be sent out for field readings.

The plates should be marked up and forwarded to the field forces in the order in which it is desired to cover the system. The variation between peak loads in different districts can be considered and in some cases certain districts can be reserved for the later part of the survey to allow for the completion of certain system arrangements, substation cut-ins, feeder changes, etc.

Procedure for Field Test Forces

Voltage surveys covering large systems involve a considerable amount of field work. Although the test procedure is no different from that of routine tests, the personnel requirements are not so readily solved and may have a material influence on the specific form of procedure adopted.

The number of field men required depends mainly on whether graphic or indicating instruments are used and the length of time over which the survey is extended. Graphic instruments require the use of more experienced testers to set up the instruments, see that the pens are inking properly, and to check the calibration of the graphic instruments. Where several graphic instruments are to be set up at a location, a crew of two men may not average more than one location per hour. Although locations may be farther apart on radial systems than on network systems, the time factor is partially balanced by the preponderance of three-phase locations on the network, which require more instruments.

In using graphic instruments, the peak-hour limitations are avoided, as the instruments are generally set for 24 hours and can be installed at any convenient time. Test crews therefore are able to spend a greater proportion of time in the field than is possible with indicating instruments, especially when readings are confined to the hours of 6:00 to 10:00 p.m.

Transportation of instruments by truck is desirable in connection with a graphic instrument survey. A light delivery truck can be used to deliver instruments at a dozen or so locations, with the field crews following by foot, trolley, or bus. A routing sheet will indicate to delivery crews and installation crews the locations to be covered by each.

The use of indicating instruments requires less time per location. The number of locations covered per man may average four or more per hour. The equipment carried by these men should be as light in weight as possible, consisting of not more than a voltmeter, leads, a small tool bag, and maps. A temperature correction curve for the voltmeter should be included as considerable variation in temperature may take place during an entire survey period, affecting readings as much as one or two volts. Indicating voltmeters should be tested daily for accuracy.

Each tester can be given a new set of maps daily, leaving the unfinished readings of several testers from the previous day to be completed by testers traveling in trucks. During severe winter weather or when taking readings in remote or scattered areas, the work can be expedited by operating multiman crews from trucks.

Each tester should make out a route record in duplicate, indicating the district in which the days work is to be done and the number of prints taken out. One copy of this should be kept for office record purposes and the other forwarded to the company's night service force to inform them of the work being done, as consumers may telephone to verify the authenticity of the tester. At the end of the day the tester should check off on the office record copy the number of plates covered, the number of readings taken on each plate, total number of readings taken, and any irregularities, however slight.

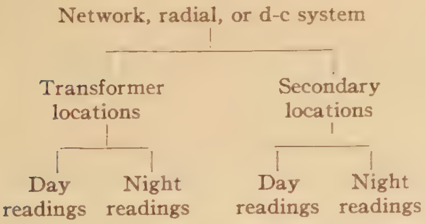
The readings recorded on the prints should be rechecked by a clerical force to see if the readings appear normal. Unusual readings should be called to the attention of the engineer in charge of the voltage survey so that an investigation of conditions can be made without delay.

Where the scale of the secondary circuit maps is such that readings cannot be entered directly thereon, this procedure can be modified to specify addresses and to record test readings on standard test forms.

Recording of Tests, Classification and Tabulation of Results

Tabulation of Readings

The readings obtained by the field forces, whether indicating or graphic, will usually be referred to distribution engineers for analysis. The data must be tabulated before they can be classified. In the case of graphic voltage charts, it is desirable to record the low and high readings for each location together with the average voltage. It is desirable that transformer readings and end-of-secondary readings be tabulated separately so that the results may be weighted according to the number of readings of each type. A number of different classifications, for each district, may be necessary, as follows:



Plotting Readings on Maps

A useful summarized record of the results of a voltage survey may be obtained by plotting the readings on a map of the territory, drawn to some small scale. Where locations are too close together to permit plotting each reading, the average may be shown, particularly if the variation is not great. Such a map is of interest to executives and to the distribution engineers in obtaining a general view of system voltage conditions. Voltage-regulation conditions on individual feeders are advantageously revealed by plotting on detailed maps of each feeder the first consumer readings of each transformer on the feeder. These maps assist the distribution engineers in studying regulation on individual feeders and on the system as a whole.

Voltage Survey Reports

The results of a systematic voltage survey may be presented in some form of periodic report. Various graphic methods are illustrated by the charts shown in figures 2*a*, 2*b*, and 2*c*. It may be desirable to contrast the results with those of the previous survey, as illustrated in figure 2*a*, to indicate improvement of system conditions. A separate chart for each district and for each type of load is usually desirable. It is also interesting to show the percentage of readings lying outside the accepted service standards as in figure 3. A tabular form of periodic report is shown in figure 4. The readings tabulated in figure 4 are the highest and lowest values as recorded on graphic charts.

Analysis and Application of Data

Engineering Analysis of Voltage Survey Readings

Whether the readings of a voltage survey are indicated directly on secondary plates, as shown in figure 1, are recorded on test forms, or are available on graphic charts filed by feeders or districts, the results should be analyzed thoroughly by the engineers in charge of the distribution system. It may be desirable to investigate further by means of graphic voltmeter doubtful high- or low-voltage conditions disclosed by indicating readings. This procedure can be extended to high and low readings one volt within the accepted service limits. All conditions

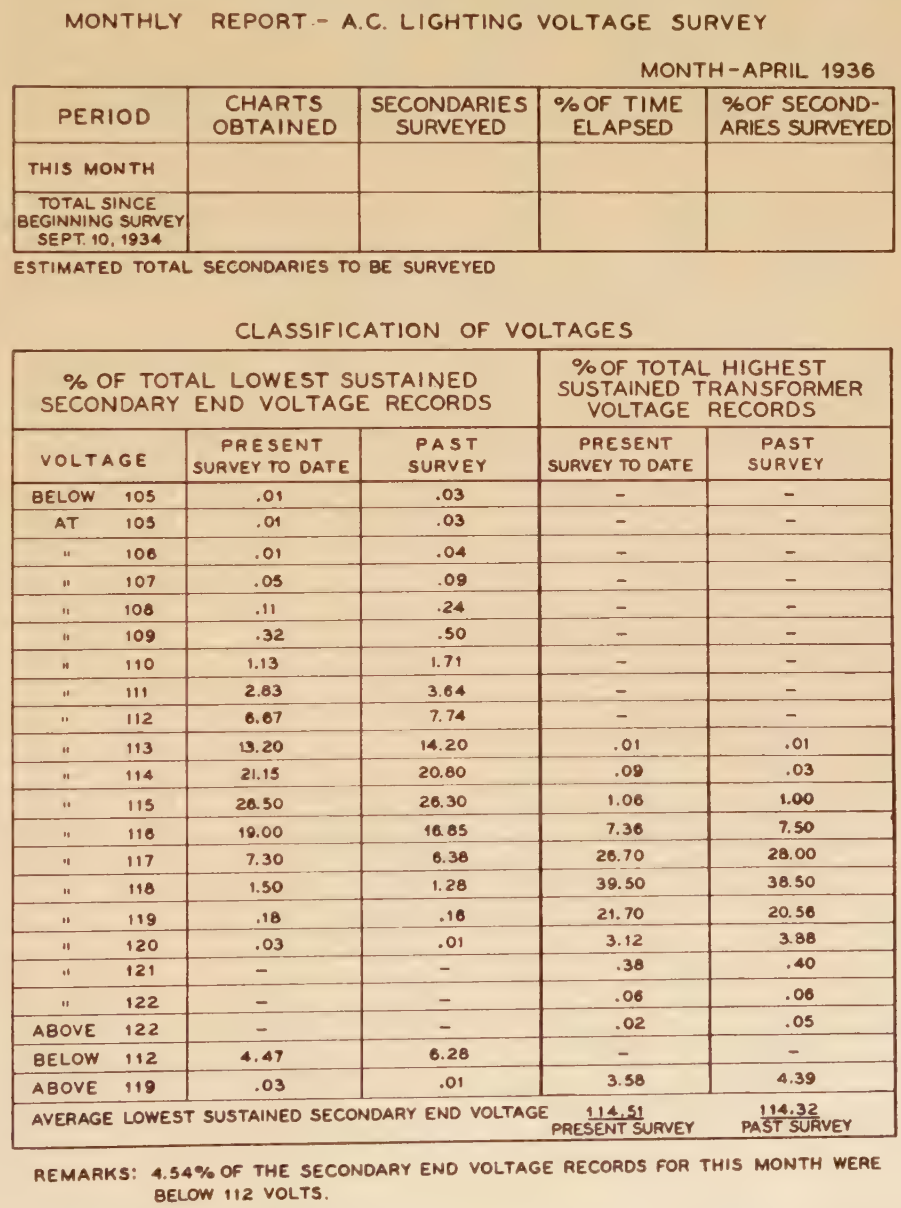


Figure 4. Monthly comparative report of voltage-survey results

MONTHLY REPORT – A.C. LIGHTING VOLTAGE SURVEY

MONTH – APRIL 1936

PERIOD	CHARTS OBTAINED	SECONDARIES SURVEYED	% OF TIME ELAPSED	% OF SECONDARIES SURVEYED
THIS MONTH				
TOTAL SINCE BEGINNING SURVEY SEPT. 10, 1934				

ESTIMATED TOTAL SECONDARIES TO BE SURVEYED

CLASSIFICATION OF VOLTAGES

% OF TOTAL LOWEST SUSTAINED SECONDARY END VOLTAGE RECORDS			% OF TOTAL HIGHEST SUSTAINED TRANSFORMER VOLTAGE RECORDS	
VOLTAGE	PRESENT SURVEY TO DATE	PAST SURVEY	PRESENT SURVEY TO DATE	PAST SURVEY
BELOW 105	.01	.03	–	–
AT 105	.01	.03	–	–
" 106	.01	.04	–	–
" 107	.05	.09	–	–
" 108	.11	.24	–	–
" 109	.32	.50	–	–
" 110	1.13	1.71	–	–
" 111	2.83	3.64	–	–
" 112	6.67	7.74	–	–
" 113	13.20	14.20	.01	.01
" 114	21.15	20.80	.09	.03
" 115	26.50	26.30	1.06	1.00
" 116	19.00	16.85	7.36	7.50
" 117	7.30	6.38	26.70	28.00
" 118	1.50	1.28	39.50	38.50
" 119	.18	.16	21.70	20.56
" 120	.03	.01	3.12	3.88
" 121	–	–	.38	.40
" 122	–	–	.06	.06
ABOVE 122	–	–	.02	.05
BELOW 112	4.47	6.28	–	–
ABOVE 119	.03	.01	3.58	4.39
AVERAGE LOWEST SUSTAINED SECONDARY END VOLTAGE			114.51 PRESENT SURVEY	114.32 PAST SURVEY

REMARKS: 4.54% OF THE SECONDARY END VOLTAGE RECORDS FOR THIS MONTH WERE BELOW 112 VOLTS.

finally determined to be above or below the accepted standards should be studied carefully to determine whether the subnormal condition is due to primary circuits, secondary mains, or service wires.

System Reinforcements Based on Survey Results

A voltage survey will disclose cases of low voltage due merely to inadequate service wires. These facilities may have been installed in accordance with old standards, inadequate for present-day loads. Such conditions are easily corrected.

Cases of unbalanced voltage will be revealed if all line-to-neutral readings are taken at each location. Some of these conditions can be corrected with little trouble by rebalancing secondary load.

Experience indicates that a high percentage of poor voltage conditions is due to the secondary mains. These conditions are indicated by analysis of the voltage survey data and may be remedied by replacing existing secondary with larger wire, by hanging additional transformers to cut down the length of secondary feed, or in some cases merely by rearrangement of existing secondaries.

In some cases low-voltage conditions can be improved by raising feeder substation voltage, provided this does not lead to overvoltage conditions elsewhere. In other cases high voltage may require lowering substation voltage.

Low-voltage conditions may be found to be due to inadequate primary circuits. Where this occurs, redesign of primary circuits may be necessary. Additional voltage readings and load readings at various points on the circuit may be necessary in such cases to provide engineers with full information. The results of the voltage survey may justify the introduction of new feeders or new substation capacity.

Where general low-voltage conditions exist over an area of relatively high load density, engineering and economic considerations may warrant changeover to underground network supply. The extension of underground network on a step-by-step basis in urban territories where all distribution is planned ultimately to be underground, is facilitated by periodic voltage surveys to disclose which areas first exceed the regulation limits of existing overhead facilities.

Conclusion

The readings of the systematic voltage survey, appropriately taken and carefully analyzed, provide the engineering justification for redesign of the distribution system to correct existing unsatisfactory voltage conditions. The periodic survey data, by revealing trends of regulation, make it possible, in planning system changes, to anticipate unsatisfactory conditions before service voltages actually fall outside the accepted standards of good service. The broad view obtained of system voltage conditions facilitates the consideration of various plans proposed, and is a helpful guide in considering the necessity for general system reinforcement and improvement projects.

It is not anticipated that a survey such as outlined in this paper need be made every year. As voltage conditions are improved, it may be found that a complete survey made every other year, or a policy of surveying a half or a third of the system each year may suffice.

Voltage Regulation and Control in the Development of a Rural Distribution System

By G. H. LANDIS
MEMBER AIEE

Synopsis: The rapid growth of rural electrification and the importance of maximum service continuity commensurate with economical expenditures has given impetus to the study of means to provide a satisfactory solution. The development of a rural network system with its sources of feed to supply this system is described. Selection of voltage rating for rural lines is often dependent upon operating conditions peculiar to the area served, and must be considered integrally with voltage regulation. Methods applicable for voltage regulation and control are reviewed with particular reference as to their application for rural line use. The economic application of regulating devices for voltage control of a rural load area is illustrated by a specific example and comparison with other means available. Methods used for obtaining a constant check of voltage conditions throughout a rural area are described and the results obtained by these means are given in a special case.

The Rural Problem

THE rapid growth of rural electrification in the past few years has stimulated activity in new methods and approach to the problem of providing adequate capacity for the present and future demands which will be made for this service. Of necessity, due to the low customer concentration, the distribution lines serving the rural areas must be constructed at a minimum cost commensurate with existing or near future usage of such service. In the United States, this has resulted almost universally in the supply of these areas by means of single-phase lines, the construction and voltage of the lines varying with the conditions encountered in the areas served, and varying with the economic, engineering, and operating conceptions of the individual utilities.

The rural area in which the Central Hudson Gas and Electric Corporation operates is probably typical of a major portion of the northern Middle Atlantic and southern New England States. The area cannot be considered strictly as a farm area. Essentially, the rural territory is a region populated by two general classes of people; first, the farmers who primarily specialize in the production of special perishable products for consumption of the large urban centers; second, small commercial and industrial enterprises in the rural centers, combined with those who have sought freedom from the city confines by temporary or permanent residence in the rural area. In the first classification, the following types of farming will dominate with their special applications of electric load:

Poultry, requiring electric service for incubators, brooders, water heating.

Stock and dairy, with milk coolers, pasteurizers, water heating, ventilating, milking machines, pumping, and general utility.

Truck and fruit, with soil heating, minor irrigation, fruit grading, insect control, spraying, pumping, cold storage.

General, with pumping, general utility.

In addition to these, the domestic usages of cooking, refrigeration, water heating, and pumping must be provided.

In the second classification, the following groups of people must be served:

Hamlets, with the country store, garage, and occasional small industrial load.

Small residential customers migrating from local urban centers.

Large residences and estates, generally drawn from the large cities.

Vacation residences, road houses and stands, boarding houses, and hotels, most of which are summer loads, but a small increasing amount is becoming either winter and summer loads, or year-round loads.

Religious, educational, and governmental institutions.

The first classification of customers requires an adequate and dependable service supply, for, in essence, they are small industrial establishments, and their livelihood is dependent upon uninterrupted service. As an illustration of the importance of continuous service, one poultry farm sells fancy stock eggs at prices as high as 40 cents each, ships quantities of these abroad for hatching, and incubates as many as 50,000 eggs at one time. An hour's interruption of the rural service to this customer may destroy a large percentage of his incubator supply.

The second classification of customers, being in a large measure people from urban territories, demand essentially the same grade of service here as that to which they have been accustomed, especially since electric service becomes more essential to their comfort and living than before.

The necessity of a high degree of continuity combined with adequate voltage control is therefore essential to the rural population. For this type of service, freedom from interruptions must be considered along with voltage control, and the choice of voltage level is in great part predicated on the ability to maintain service with the greatest freedom from interruptions.

The Rural System of the Central Hudson Gas and Electric Corporation

The franchise area supplied by the Central Hudson Gas and Electric Corporation is shown in figure 1, roughly extending 75 miles north and south along the Hudson River between New York and Albany, and 55 miles east and west, a small portion to the east bordering the state of Connecticut. The territory covers approximately 2,600 square miles and has over a quarter of a million inhabitants. The three largest cities, Poughkeepsie, Newburgh, and Kingston along the Hudson River, account for a total population of less than 100,000. Numerous villages are located throughout the area. Scenically magnificent in the mountainous regions of the Catskills and Shawangunk Mountain Ranges, beautiful for its well-kept farms and orchards, and within close driving distance of the great metropolitan areas, it attracts many thousands of vacationists.

The general layout of the Central Hudson electrical system is shown in figure 1. The company, having developed only a small amount of generating capacity (25,000 kw in water power, and 12,000 kw in steam) is dependent upon the supply of power over strategically located transmission interconnections. A well-located transmission system at 66 kv ties its main load areas into an integrated system, supplemented by secondary transmission feeders and tie lines

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1. For all numbered references, see list at end of paper.

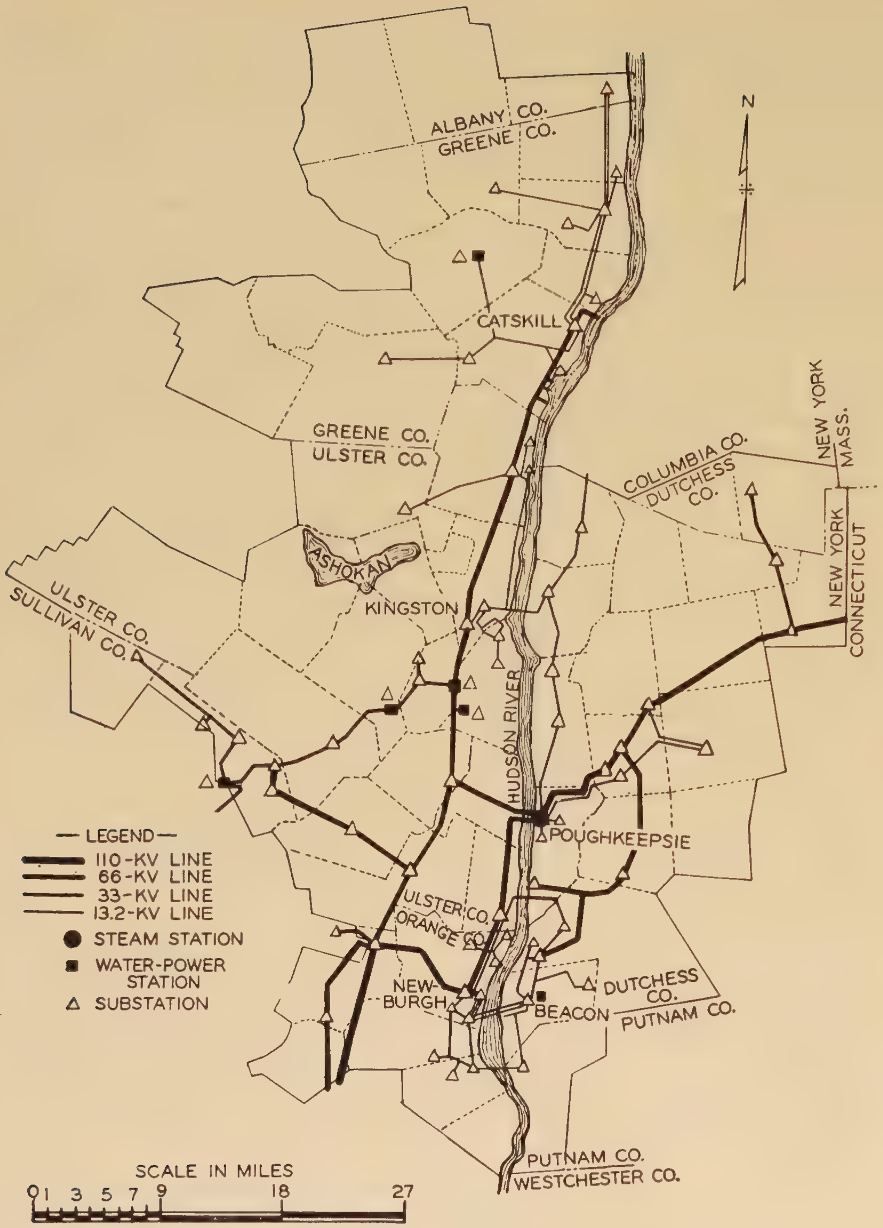


Figure 1. Franchise area showing transmission lines, steam and water-power stations, and substations

at 33 and 13.8 kv, thereby forming a fairly well-defined grid over the entire area.

Among the pioneers in recognizing the necessity, desirability, and value of rural electrification, the company initiated its rural-line program in 1924 and has maintained an aggressive and liberal policy for the development of rural loads. An accelerated program during the last two years has brought about virtual saturation of the area with rural distribution lines, these lines now being within reach of 98 per cent of the rural population. A total of over 2,700 miles of rural lines has been built in the rural construction program, to which have been attached some 6,000 farm, 25,000 residential, 5,000 commercial and small industrial customers. The usage per rural customer averages 1,650 kilowatt-hours annually, but may be expected to increase rapidly since customers on recently constructed lines first make use of electricity primarily for lighting and later take full advantage of a liberal policy on the purchase of electrical appliances.

A typical rural area showing the coverage of highways in a rural section is shown in figure 2. Practically all roads not supplied by distribution lines have a load density of less than three customers per mile.

Power supply to the rural areas has been planned upon the projection of a number of small automatic substations upon the grid formed by the network of rural lines. Theoretically, such an area would appear as shown in figure 3, resembling in many respects a primary network grid. However, several distinct factors differentiate the plan from a primary network. Three-phase tie lines are generally provided, or are anticipated between substations, these being constructed if, and when such tie lines are economically justified. This construction consists of polyphasing existing single-phase lines, such single-phase lines later to form tie lines having been built of greater conductivity size in anticipation of their future tie-line application. At the present time plans do not contemplate the operation of the tie lines closed, these being operated as radial feeders from each substation. Their main purpose is to provide facilities for emergency feed into an area in the event of a substation failure, or in case of the necessity of taking a substation out of service for routine maintenance. Routine maintenance is necessarily scheduled for off-peak periods. In case of a substation failure during peak periods, lower voltage than normally considered fully adequate would be experienced, but service could at least be maintained. This latter condition has not yet been experienced on our system, and should be relatively infrequent. Future development may show the possibility of operating the rural network as an integrated network, as recently accomplished in a section of suburban Philadelphia.[1,2] Figure 4 shows a portion of such a development showing the location of stations and tie lines.

The locations of substations to supply this rural network are necessarily influenced by a number of factors, as follows:

1. Load density of the area to be supplied.

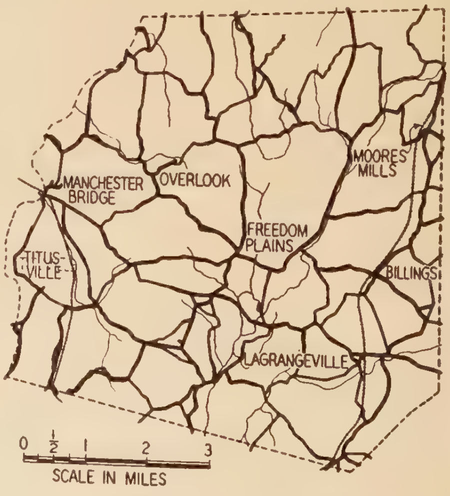


Figure 2. Typical rural area showing coverage of highways

2. Proximity to existing transmission lines. Wherever possible, advantage is taken of existing lines and switching structures in such lines. Substations are tapped through suitable protective equipment to lines of any voltage available, 13.8-, 33-, and 66-kv equipment having been used.

3. Proximity to villages or industrial loads.

Various types of substations have been utilized, the type depending to a great extent upon the following factors:

1. Probable load growth in the immediate area.

2. Possibility of load shift as area is developed.

3. Availability of existing equipment, which may be transferred from some other substation due to necessary changes in that location.

During the early periods of development, when the number of rural lines in an area were limited, a number of two- or three-pole platform structures both with and without regulators were installed. These have mostly been replaced by more adequate equipments, and at the present time there appears to be little need for the use of this type of structure, since it is usually possible to pick up an immediate load of 400 to 500 kw by the time a substation is required in a rural area.

New substations are now installed with a capacity of 750 to 1,000 kva with the possibility of increasing these ratings 25 per cent with air-blast equipment. They are tapped to the transmission line through a manual three-pole disconnect switch and protected on the high-voltage side by means of fuses. Voltage regulation is provided in new transformers through tap-changing equipment. Where existing transformers are available, regulation is supplied by means of step regulators, pole-type or outdoor substation-type induction regulators, or indoor induction regulators rebuilt for outdoor service, the type used depending upon the equipment available.

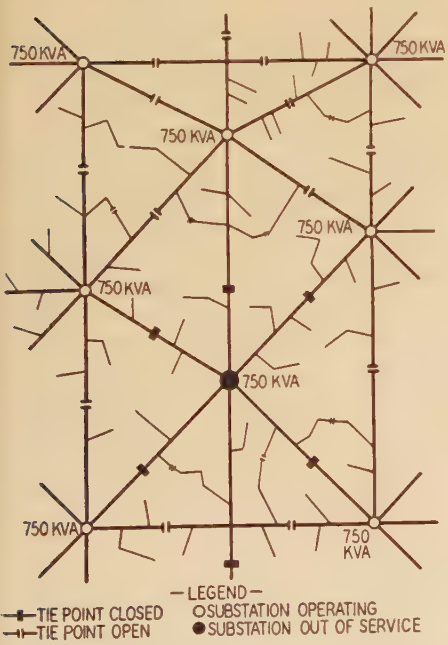


Figure 3. Theoretical rural network showing polyphase tie lines between substations, and operation with one substation out of service

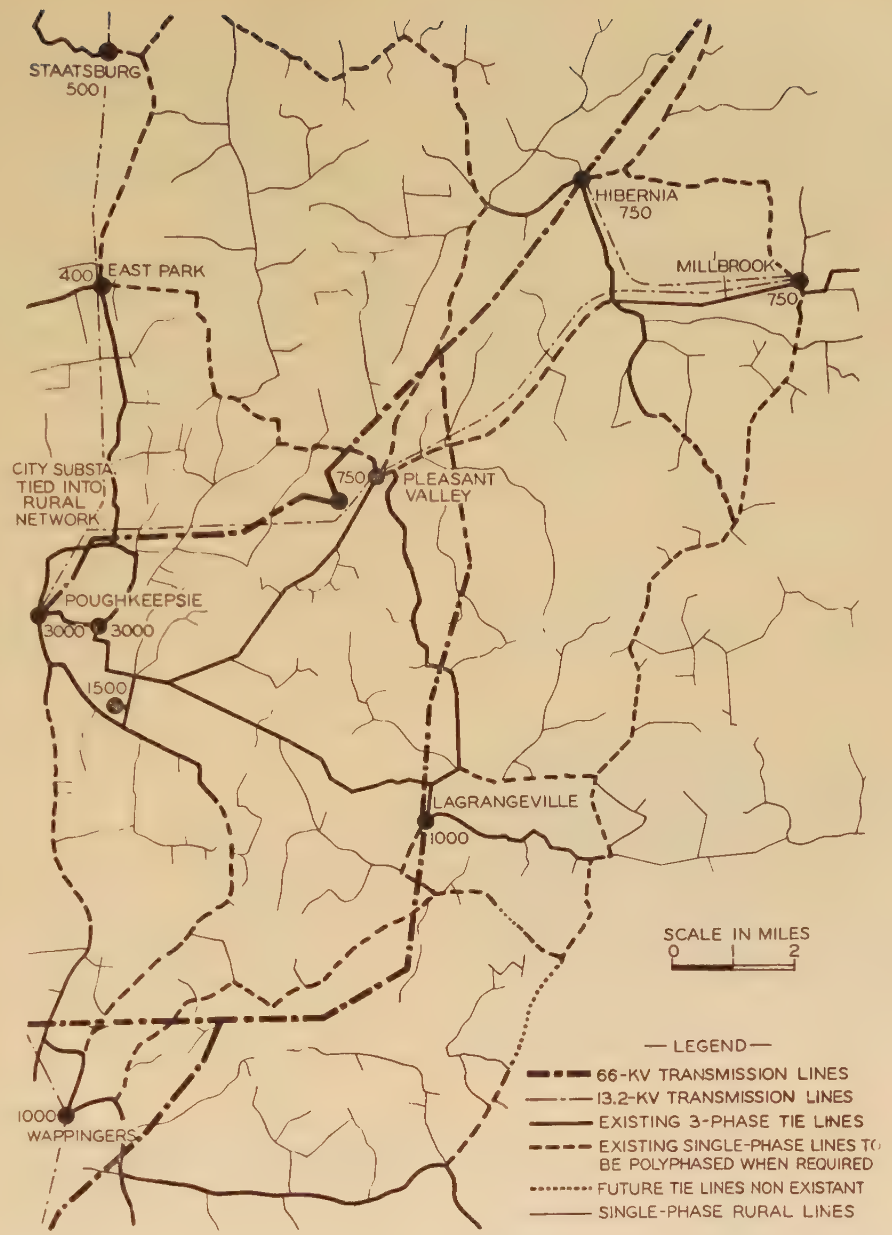


Figure 4. Development of rural network showing substation and tie lines

Where new equipment is required, a unit-type substation has been adopted as standard equipment. The first unit was installed in 1931, and has been followed by the installation of three additional units. The 1938 program calls for the installation of three units, one to be ready for service by the end of May.

The essential requisites for a unit substation are as follows:

1. The total installed cost must be low, comparing favorably with the cost of the conventional structure substation.

2. The unit must provide voltage regulation to compensate for transmission and primary voltage drops.

3. It must be inconspicuous, require a minimum of space, and present a minimum hazard from public liability standpoint.

4. The installation cost must be low, thereby providing maximum salvage in the event it becomes necessary to shift the location due to a change in load distribution or development.

5. It must be easily and safely maintained. In the event of breakdown of any piece of apparatus, particularly the transformer, the layout must allow for its ready removal and replacement.

6. The design must provide economical

means for adding feeder positions, in the event load conditions make this necessary.

The design which was developed meets all these requirements. Essentially, it consists of a tap-changing transformer, with one or more switch houses bolted to one side of the transformer. The switch house contains a reclosing oil circuit breaker and load-ratio-control equipment. High-voltage fuses and disconnects are installed in compartments on the transformers rated 23 kv and lower. Our practice has been to bring all cables to and from the pole line underground, for voltages of 23 kv and lower, thereby enclosing all equipment in metal, and obviating any necessity for fencing in the property for safety reasons. For the higher voltages, a simple superstructure permits overhead connections. The unit is completely factory built, the only field construction consisting of foundations and connections to the lines. Floor space requirements for the unit are approximately 10 by 13 feet.[3]

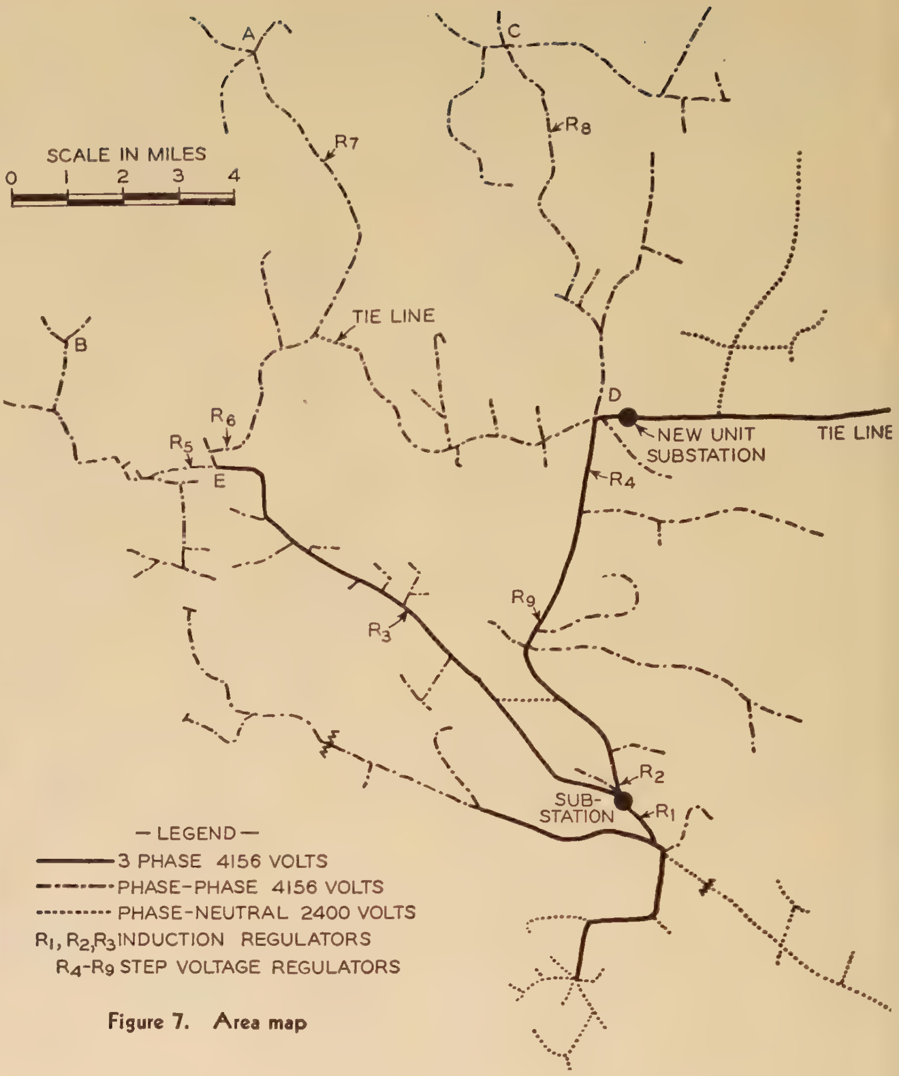


Figure 7. Area map

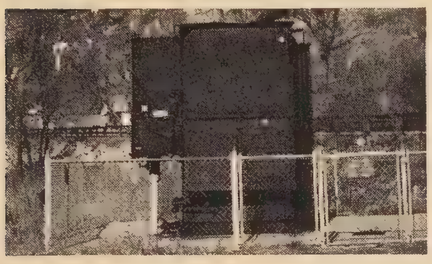


Figure 5. Medium-voltage totally enclosed unit substation, rated 750 kva, 13.8–2.4/4.16 wye/4.8/8.3 wye kv

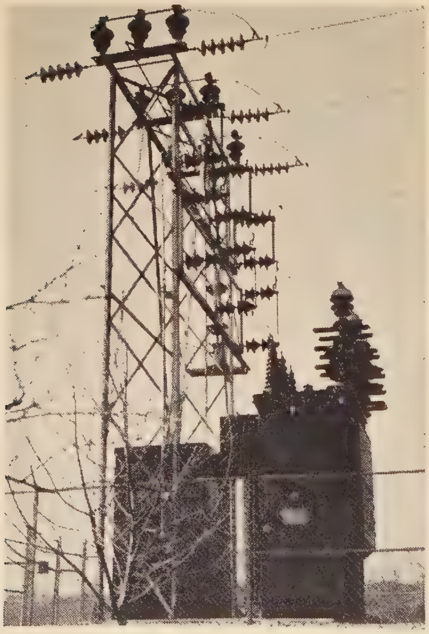


Figure 6. High-voltage unit substation with superstructure for high-voltage control, rated 1,000 kva, 66–2.4/4.16 wye/4.8/8.3 kv

The simplicity with which one of these units may be moved, is illustrated by a case in which it was necessary to move a 750-kv unit complete with feeder equipment, approximately four miles. The unit was available for operation within two working days, including a change in internal connections from 4,800 volts delta to 4,160 volts wye.

Figure 5 shows a typical unit substation rated 13.8 kv, 750 kva, with all live parts metal clad. Figure 6 illustrates a 66-kv 1,000-kva unit with exposed high-voltage switching on a steel superstructure. The air-break switch on top of the structure and the capacitor on the side have no relation to the unit structure, being automatic sectionalizing equipment for the 66-kv transmission line.

Voltage Rating of Rural Lines

The selection of voltage rating for rural lines is dependent on many factors, and the economics of a voltage rating in one part of the country may well be reversed in others. Obviously, a high voltage rating simplifies the problem of voltage regulation.

The Central Hudson Gas and Electric Corporation, being a consolidation of many smaller companies, inherited a number of voltage ratings at both two and three phase from its predecessor companies. Involved as the system is with numerous polyphase loads in the villages scattered throughout its rural area, the problem of unifying the voltage rating has been a slow and arduous one, since the unification of voltage ratings and phases has only been accomplished as the operation and economics have proved the necessity for changes. The present and probable future status of rural voltages in per cent of total load is shown in table I.

From this table, it will be noted that standardization in general will be at two voltages; 4,160-volt, three-phase, four-wire mains with single-phase branches at 2,400 volts phase to neutral and 4,000 volts phase to phase, 4,800 volts single and three phase. A limited area will, in

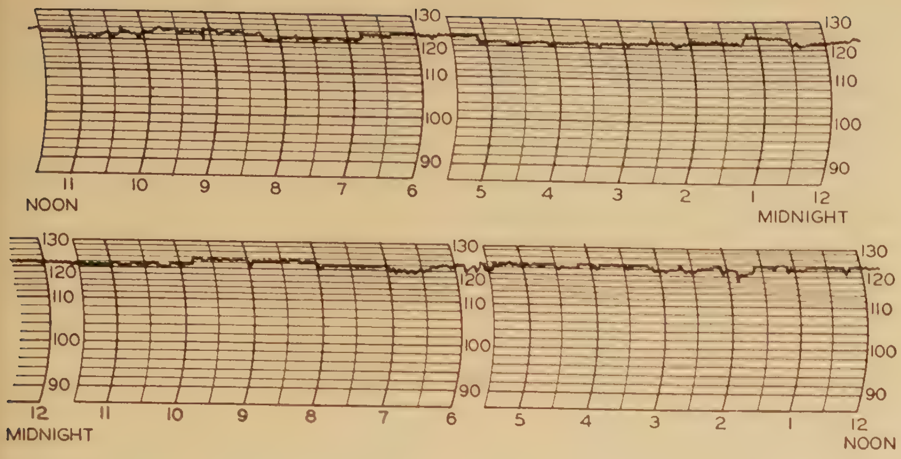


Figure 8. Typical 24-hour chart—primary voltage at point A

all probability, remain at 8,320 volts, three phase, four wire, with branches at 4,800 volts phase to neutral, or at 2,400 volts phase to neutral, the reduction in voltage being obtained through 2:1 autotransformers.

It will be noted that the company's experience has covered a wide range of voltages. Beginning initially with 2,400-volt two- and three-phase systems, conversions were made first to 2,400/4,160 wye operations, and at a later date to some 4,800-volt systems. A trial installation at 4,800/8,320 wye was also made. This has been successfully operated, but was found to have definite operating disadvantages for conditions encountered in our particular area. For sparsely settled areas where clearances from trees can be readily obtained, and where economic joint usage with communication facilities can be satisfactorily negotiated, there appears to be a distinct field for its application.

Consideration of the factors involved in the analysis of our rural problem has led us to the conclusion that the most satisfactory voltage for rural distribution in our area is 2,400/4,160 wye volts, three phase, four wire with common-neutral multiple-grounded construction. However, since some of our areas are operating at 4,800 volts, delta, there does not appear to be sufficient justification for conversion of such areas to the common neutral system. Hence the dual standard.

Table I. Distribution of Rural Voltage Ratings

Voltage Rating	Present		Ultimate
	Connected Kilovolt-amperes	Per Cent of Total	Per Cent of Total
2.4 kv, three phase delta	3,571	6.4	...
2.4 kv, two phase	4,721	8.5	...
4.2 kv, three phase wye	32,196	58.3	72.0
4.8 kv, three phase delta	11,977	21.8	25.0
6.2 kv, three phase wye	1,460	2.6	...
8.3 kv, three phase wye	1,333	2.4	3.0
Total	55,258	100.0	100.0

The decision on the adoption of the common neutral 2,400/4,160 wye system was primarily based upon the following factors:

1. Spacing of substations in the fully developed plan will provide rural feeders of reasonable length for adequate primary regulation, especially with the judicious use of step regulators and shunt capacitors in providing economical and satisfactory means of voltage control.

2. Advantages of a common-neutral system in obtaining better operating characteristics in:

(*a*) Lightning protection of distribution transformers as shown by the analysis of outages from this cause.

(*b*) Low ground resistance of the neutral wire through multiple grounding.

(*c*) Simplification of all line and transformer devices.

(*d*) Improvement in sectionalizing and branch fuse operation.

3. Safety in live-line maintenance, due to voltage being well within the safe operating range of standard rubber goods.

4. Minimum of trouble due to tree interference. This factor is particularly important in this region, due to the difficulty of obtaining permission for ample clearances from trees in a territory prolific in its abundance of large and old trees. The common-neutral system also permits the economical use of cable construction through the use of self-supporting cable or cable supported on a neutral conductor messenger where tree conditions prevent successful operation of tree wire.

5. Economic analysis indicates that this system can be used at costs comparable with systems of higher voltages.

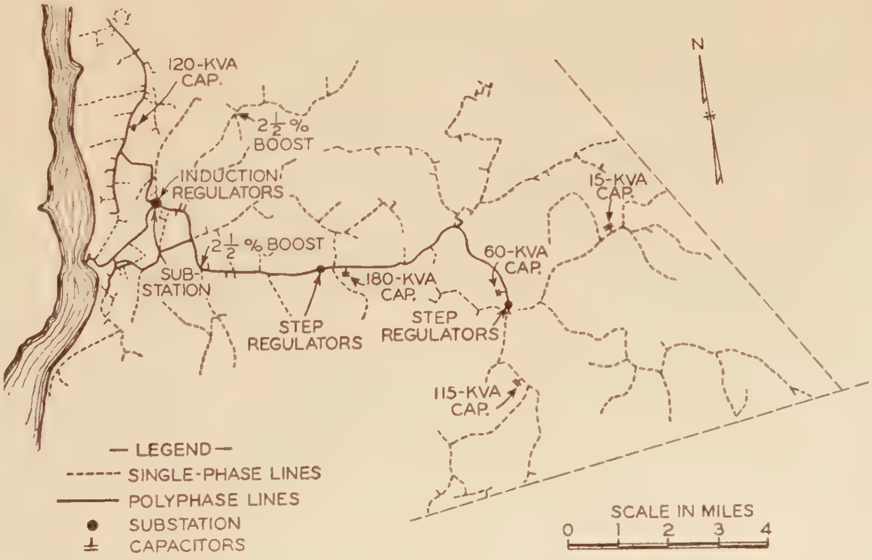
Development of a Rural Area

In the development of a rural area, it is by no means unusual to attach rural lines of extreme length to a substation supply source. During the initial period, the loading on these lines may be extremely light, gradually increasing with the attachment of additional customers and the further utilization of the service. The development of low-cost regulating equipment has materially increased the time limit before additional reinforcement becomes essential. The use in particular of step regulators and automatic boosters may lengthen the period of adequate regulation on a rural circuit for years. One of the big advantages of this class of equipment is that the cost of installation is a small percentage of the total cost and a large part of the cost in equipment is salvageable.

Thus it may be economical to use regulating devices on the lines to furnish temporary relief for any one of the following reasons:

(*a*) To allow further study to be made to

Figure 9. Circuit map



determine the most desirable and economical permanent solution.

(*b*) To allow further development of the area supplied before definite plans are put into effect which may be affected by these developments.

(*c*) To delay the expenditure necessary to accomplish the ultimate plan until economically warranted.

These points are, of course, interrelated and whichever may be the primary reason for the use of regulating devices, the other advantages will be gained.

A description of such a development in one of our rural areas has been presented previously[4] but it may be of interest to trace the development through its successive stages.

Figure 7 shows the area under discussion. Originally supplied at 2,400 volts single phase, lines were extended and supply reinforced through the following stages:

Polyphase of main stems at 2,400 volts (1924–26)	peak load 250 kw
Conversion to 4,000 volts (1927)	peak load 325 kw
Addition of two pole-type induction regulators and several fixed boosters (1929–34)	peak load 700 kw
Relocation of existing regulators and additions of six step regulators, resulting in four step regulators in series on one feeder (1935)	peak load 750 kw

The addition of step regulators in 1935 was estimated to provide regulation for the system through 1937 for an estimated peak of 950 kw. Actually, with the installation of an additional polyphase step regulator installation on one of the branches, adequate voltage was maintained with an actual peak of 1,100 kw.

Figure 8 is a primary voltage chart taken at the end of one of the lines, $19^1/_2$ miles from the substation, regulation being obtained through four regulating devices in series.

In 1938 a unit-type substation is being installed at location *D*, which together with an additional tie line, will take up approximately 500 kw of load from the original station, and will practically halve the length of the longest circuits.

In 1935, when the decision was made to install step regulators, a detailed investigation was made into the cost of reinforcement to this area, with the following comparison:

Plan 1. Changeover system to higher distribution voltage (8 kv)	$45,350.
Plan 2. Additional 13.2-kv substation, and necessary transformer and feeder extension	40,500.
Plan 3. Installation of step regulators and feeder reinforcement	15,700.

As a result of the adoption of plan 3, the following points of economic interest were obtained:

1. Investment not salvageable or useful when plan 2 would be essential for capacity	$3,000.
2. Saving in fixed charges by adopting plan 3 for three years at 12 per cent annually, less nonsalvageable items, less increase in losses due to adoption of plan 3	4,400.

The adoption of the step regulator plan was not only the most economical but also postponed the necessity of making a much larger immediate investment, and gave three additional years for the region to develop so that advantage could be taken of changes in load distribution in the area.

Voltage Control and Regulating Devices

No attempt will be made here to present the technical details of operation, or the theoretical limits of applications, as this subject has been fully covered in numerous papers previously.[5–7] A brief outline of the devices available, and their adaptability to rural-line application appears in order.

For strictly rural load, consisting mainly of a multiplicity of comparatively small individual loading devices, the use of high-speed devices for following small voltage fluctuations appears to be unnecessary. A number of tests on the effect of time delay conducted on our regulating devices indicate that the number of operations of tap-changing equipment may be reduced approximately 80 per cent by increasing the time delay from 10 to 30 seconds, with no appreciable effect on the voltage regulation. The step regulator, in which time delay between steps is inherently necessary, has proved to be the most adaptable equipment for general application due to its low initial and installation costs. Careful consideration must be given to the voltage range per step. No specific limits can be definitely stated as to the most economical and satisfactory range of steps, and each application must be considered on its own merits. Generally, for rural loading four $2^1/_2$-per-cent steps appear to provide a satisfactory range for adequate voltage regulation.

The automatic step booster has a very limited application for rural loading, and its application is usually dependent upon comparatively large changes of load connected for appreciable periods of time.

The fixed booster, though obviously not a regulating device, still has a definite field in voltage control. By their use, a line can be controlled to have practically flat regulation at minimum load conditions, and such use has practically the same effect as obtained by increase in size of copper. The amount of boost can be readily controlled by the use of multiple-ratio distribution transformers, and if a standard make transformer rated 2,400/3,600/4,156/4,800–120/240 volts is used, voltage boosts of 2.5, 2.88, 3.33, 5.0, 5.76, 6.66, and 10 per cent may be obtained on a 2,400-volt primary line.

The application of shunt capacitors for voltage control on rural lines has little justification, except where it is possible to make use of the advantages obtained by the capacitor in releasing substation transformer or transmission-line capacity, or in system power-factor correction. The low installed cost of distribution capacitors compares favorably with the installed cost of reasonably large rotating equipment, and where a certain fixed amount of capacity may be economically used at all times, distribution capacitors with their much higher efficiency, may readily be justified. The amount of voltage control supplied by these devices being fixed within narrow limits (two to three per cent on rural lines), they must

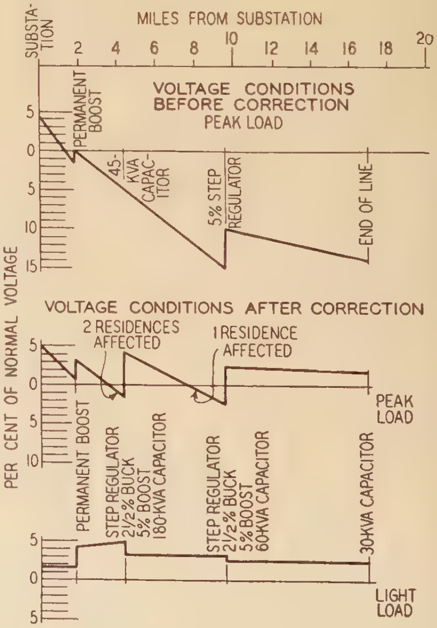


Figure 10. Application of voltage-corrective measures following graphic instrument survey of rural-line loading and regulation

be applied with the same caution as the fixed booster.

The series capacitor can rarely be applied for rural-line regulation. Depending upon the elimination of the reactance drop by insertion in the line of a capacitive reactance equal to the inductive reactance of the line, its purpose is defeated by the large resistance component of the average rural line. Elimination of the reactance drop is insufficient as shown by table II.

By overcompensating, part or all the drop due to resistance can be balanced out at any power factor other than unity. At high power factors, this requires an unreasonable amount of capacity. The series capacitor may be compared to an instantaneous regulator set to maintain a fixed voltage at some load center (assuming the supply voltage constant). It is subject to limitations where customers are distributed along the line in that any decrease in drop effected for the last customer on the line is accompanied by a corresponding increase for the first customer. This can be overcome by splitting the capacity up in small-size units, but only at prohibitive cost.

Except in those cases where instantaneous regulation is required to overcome a flicker condition or where lines are used to feed a load at some distance with no intervening load, some other one or combination of devices will give more satisfactory or economical results than the series capacitor.

Voltage Surveys

In order to keep a constant control of voltage conditions throughout the territory, a program was started several years ago of installing permanent voltage-recording stations attached to the primary lines through individual potential transformers. Completion of this program is expected during 1938. The location of each of these test stations is carefully checked to provide a close control and indicator of the voltage and load trend.

In addition, a plan of conducting periodic surveys of all load areas has been instituted. This survey covers the procurement of a complete series of simultaneous graphic records of voltages over the entire area, coupled with graphic ammeters at pertinent points for loading and load balance, and graphic wattmeters and reactive-volt-ampere meters for circuit loading. These charts, assembled and pasted together, show simultaneous readings all over the circuit, and readily reveal the necessity for load balance, reinforcement, correction for regulator settings, and improvements which may be effected through the use of additional boosters, step regulators, and shunt capacitors. This recording is continued until corrective measures have been applied and reasonable assurance is obtained from graphic records that voltage conditions will continue to be satisfactory. In conducting such a survey 20 to 30 graphic voltmeters are utilized, these instruments being calibrated in the field after warming up in location, a high-grade voltmeter with low temperature error being used for this calibration.

An illustration of the effectiveness of this field survey is shown in an area which had built up very rapidly in rural extensions, and which had not received a previous check of the type described. Figure 9 shows the area in question and figure 10 shows the voltage conditions before and after voltage conditions were corrected. In this case four additional step regulators and 165 kva in shunt capacitors, provided adequate relief from the serious voltage difficulties encountered. Further improvement to this area, contemplated several years previously, will be provided when the fringes of this area can be transferred to a new unit substation to be installed in 1938.

Conclusions

The necessity of reliable rural lines with adequately controlled and regulated voltage has been shown to be essential for the type of service requirements. Voltage rating is dependent upon many factors, and reliability and freedom from interruptions must be considered along with voltage rating. With the equipment now available, voltage can be accurately regulated over substantially long lines at reasonable cost, and frequently major expenditures for reinforcement can be deferred for long periods by the proper application of regulating equipment. The field for application of step regulators is large and due to the low installation cost may be justified in many cases for temporary relief. The application of shunt capacitors is more restricted on rural lines where resistance drop may be a large portion of the total drop, and cannot be justified for voltage regulation alone, but may be used where interrelated savings in substation capacity or system power-factor improvement aid in the justification of their use. Series capacitors appear to have little application for general rural use, and their justification is dependent on special applications usually in conjunction with motor loads.

Table II. Voltage Drop on Four-Kv Three-Phase Line

Copper Wire Size	Volts Per Ampere Per Mile at 85 Per Cent Power Factor: Due to Resistance	Due to Reactance	Total
2	.66	.38	1.04
4	1.17	.39	1.56
6	1.67	.40	2.07

Rural electrification, being still in its infancy with respect to utilization, requires continual and careful study and checking of load growth, circuit balance, and voltage regulation to the end of producing greater satisfaction among its users, increased revenues from adequate regulation, and stimulating the further utilization of the service available.

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Voltage-Regulating-Equipment Characteristics as a Guide to Application

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Synopsis: In addition to being based on economic factors, the application of voltage-regulating equipment to systems should take into account its characteristics and inherent limitations. These characteristics include operating speed, sensitivity, suitability for parallel operation and for frequent voltage-correcting action, how affected by the load power factor and by line constants, ability to compensate for supply-voltage variations, effect on wave form, etc. The majority of systems need both generator voltage regulators and suitable feeder regulators, if maximum ease, efficiency, and flexibility of system operation are desired. Proper choice and adjustment of the voltage-responsive controlling elements of such regulating equipment will insure harmonious functioning of the regulators throughout the system, without hunting between regulators of different construction.

THE selection of voltage-regulating equipment involves two classes of problems. The first of these is technical, and concerns itself with the characteristics of the various available classes of regulating equipment with their corresponding limitations. The second problem is economic and is concerned with finding the least expensive solution to the problem of maintaining adequately constant voltage. The economic problem predominates in the application of voltage-regulating equipment to the distribution system,[1] as distinct from the generating and transmitting portion of the system. As far as the technical characteristics of voltage-regulating equipment are concerned, it might be felt that these are too well recognized to require further consideration at this time. However, instances frequently occur of misapplication of regulating equipment due to disregard of the inherent limitations of the types of regulating equipment concerned, usually because insufficient consideration has been given to the analysis of the causes of the poor voltage conditions which it is desired to correct.

As here used, the term "voltage-regulating equipment" signifies not merely the voltage regulator itself but also the associated apparatus such as for example, a synchronous condenser when controlled by an automatic voltage regulator.

Only equipment that functions automatically is here considered.

As above defined, voltage-regulating equipment is subjected to supply-voltage variations due to transient conditions such as those caused by faults and also to those produced by slow or rapid load changes. (By load changes are meant not only changes in the amount of steady load connected, but also noncyclic, abrupt changes in load impedance, such as may result from the starting of large motors connected with the circuit and from similar causes.) Voltage-regulating-equipment performance during fault conditions and its effect on stability[2,3,4] will not be discussed here, nor will the subject of voltage variations due to cyclic changes be discussed at this time.

Progress in industrial and domestic electrification has gradually imposed added requirements upon the quality of electric service, such as the present-day insistence on maintenance of sufficiently constant frequency for electric-clock operation. Fortunately, however, this tendency toward more exacting electric-service requirements is to some extent compensated for by the improvement of apparatus. For instance, the advent of adequate generator voltage regulators made it possible to discontinue insisting upon small natural voltage regulation as a generator design requirement. This change makes it possible for generator designers to emphasize other more important characteristics of their machines. It is believed that by proper application of voltage-regulating equipment to a system, the range of taps required in transformers can be kept within economical limits, thereby reducing the investment in what would otherwise be special power transformers. Also maximum freedom in system operation is afforded so that the voltages at different points on the system can be held at the most appropriate values from the standpoint of minimizing transmission line losses and keeping the power factor within the desired limits in interconnecting lines.

Classification of Voltage-Regulating Equipment

Voltage-regulating equipment may be classified on the basis of the manner in which it functions, as shown in table I.

As used in this tabulation, the term "generator voltage regulator" means, according to a proposed standard definition, "a regulator which functions to maintain the voltage of a synchronous generator, condenser, motor, or of a d-c generator, at a predetermined value, or vary it according to a predetermined plan."

The question of whether extensive use should be made of generator voltage regulators in preference to the use of feeder voltage-regulating devices sometimes arises, but except in special cases of systems of very limited extent, a definite choice between the two types of equipment should rarely be necessary. Generator voltage regulators are, by virtue of their construction, usually better suited to rapid and frequent operation than are feeder voltage regulators, if maintenance of the latter is to be kept within reasonable limits. Generator voltage regulators are, however, electrically farthest away from individual

Table I

(*A*) Voltage-correcting equipment (corrects for supply-voltage variations)
  (*a*) Direct (series) correction
    Varying excitation (generator voltage regulator) .... (1)
    Varying voltage ratio
      I. With major change in voltage level (Load-ratio-control transformer)............... (2)
      II. Without major change in voltage level
        A. Smooth changes
          (Station-type induction regulator).............. (3)
          (Branch-feeder induction regulator)............... (4)
        B. Changes by steps
          (Regulating transformer).. (5)
          (Station-type step regulator).................. (6)
          (Branch-feeder step regulator).................. (7)
          (Branch-feeder booster).. (8)
  (*b*) Indirect (shunt) correction
    (Synchronous condenser with voltage regulator).............. (9)
    (Shunt capacitors with voltage-regulating relay).................(10)
    (Shunt reactors, in blocks, with voltage-regulating relay).........(11)
    (Shunt reactors with saturating windings).......................(12)
(*B*) Voltage-drop compensating equipment (does not correct for supply-voltage variations)
  (*a*) Direct (series) compensation
    (Series capacitors)...............(13)
    (Series reactors with saturating windings)........................(14)

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[1] For all numbered references, see list at end of paper.

loads responsible for fluctuations in the voltage. Thus there appears to be little relationship between the speeds of operation of these devices and the duty ordinarily imposed on them. This dilemma can be avoided by proper adjustment of the sensitivity of the voltage-responsive control elements of the generator and feeder voltage-regulating equipment, respectively. In general, it may be said that:

1. The need for rapid correction of the voltage in case of major system load changes makes generator voltage regulators essential for most systems.
2. The value of generator voltage regulators in limiting overvoltage in case of sudden loss of load is now well recognized.[5]
3. The impracticability of applying line-drop compensating schemes to most systems to permit generator voltage regulators to hold constant voltage at a remote distribution center makes feeder regulators desirable.
4. The diversity of feeder lengths and loading makes the application of individual feeder regulator equipment of appropriate type essential to good voltage conditions at the load.

It is hoped that a brief discussion of the comparative characteristics of each of the voltage-regulating equipment types mentioned in table I will be of assistance to anyone faced with the problem of choosing between the available means for solving this problem.

Generator Voltage Regulators (1)

These regulators are best suited to holding constant voltage at the low-voltage or high-voltage generating station bus. Although it is possible to use line-drop-compensating schemes to hold constant voltage at the remote end of a transmission line, there are very few cases in which as much line-drop compensation as this is used. The basic reason for this is that changing load and generating conditions on a system make it desirable to hold different voltage levels at different points on the system at various times of the day. Compensating for all of the transmission-line voltage drop makes it difficult to control the division of reactive power between different generating stations and is comparable to attempting to operate two generators, each under voltage-regulator control, connected to the same bus without having the usual provision for eliminating excessive reactive-current interchange between the two generators.[6] The use of motor-operated voltage-adjusting rheostats for generator voltage regulators in unattended stations makes it possible to adjust the voltage levels held at such stations by means of supervisory control just as readily as the kilowatt load on units in such unattended stations can be adjusted.

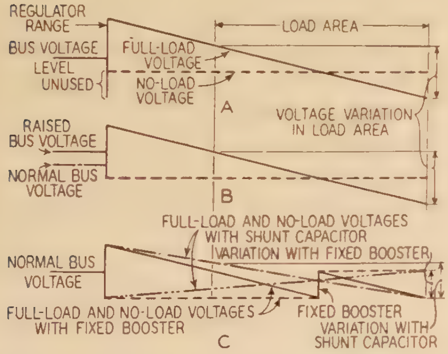

REGULATOR RANGE
BUS VOLTAGE LEVEL UNUSED
FULL-LOAD VOLTAGE
NO-LOAD VOLTAGE
LOAD AREA
A
VOLTAGE VARIATION IN LOAD AREA
RAISED BUS VOLTAGE
NORMAL BUS VOLTAGE
B
FULL-LOAD AND NO-LOAD VOLTAGES WITH SHUNT CAPACITOR
VARIATION WITH FIXED BOOSTER
NORMAL BUS VOLTAGE
FULL-LOAD AND NO-LOAD VOLTAGES WITH FIXED BOOSTER
FIXED BOOSTER
VARIATION WITH SHUNT CAPACITOR
C

Figure 1. The induction regulator inherently has a lower as well as a raise range. Full use can be made of the total range by the proper selection of substation bus voltage (B) or by the use of a fixed boost in the feeder circuit (C). Shunt capacitors produce a voltage rise, and in this case if the voltage rise produced by the capacitor equals the lower range of the regulator, full use can be made of the full regulator range with minimum voltage variation in the load area

In special cases, current limiting relays have been used in conjunction with generator voltage regulators, but it should be recognized that any such supplementary equipment may impair the normal regulator performance during transient conditions. Some use has also been made of power-factor regulators, especially when applied to generators of relatively small size located electrically close to much larger stations, with a view to avoiding attempts on the part of the small machines to change the voltage level of the larger systems and in so doing overload themselves. The use of such power-factor regulators would seem to be extremely limited and ordinarily requires supplementing by the use of a conventional voltage regulator in order to take control away from the power-factor regulator in case of faults on the system. The low power factor of most faults would otherwise cause the power-factor regulator to reduce the generator excitation, which is just the opposite of what is required under these conditions.

The use of generator voltage regulators relieves the station operator of the need for frequent adjustment of the excitation; if there are no generator voltage regulators, the only alternative is to leave sufficient excitation on the machine to insure reasonably stable operation under any anticipated load condition. This additional excitation will result in added losses and heating of the machine.

Although generator voltage regulators are, in general, rapid in action, it should be realized that even if there were no time delay at all in the operation of the regulator, it could not possibly cure light flicker in the case of voltage fluctuation sufficiently widespread to appear at the generator terminals. The first drop in voltage occurs instantaneously, but can only be corrected at a finite rate in accordance with the time constant of the a-c machine. Other methods of mitigating light flicker should be considered instead.[7]

Load-Ratio-Control Transformers (2)

Although originally chiefly used in transmission-line loop circuits and in tie-lines interconnecting different systems, increasing recognition is being given to the suitability of load-ratio-control equipment for maintaining approximately constant voltage at a bus whenever this can be accomplished by ratio change. In general, the load-ratio-control equipment is not intended for very frequent operation, in the interest of reducing maintenance on the tap-changing equipment. Accordingly, the automatic relay equipment ordinarily includes time-delay relays to insure that the departure from normal voltage must persist for a definite time before any attempt is made to correct it.

Station-Type Induction Regulator (3)

The characteristics of the direct or series regulating device used for feeder regulation are a combination of the inherent characteristics of the equipment itself and the control with governs its operation. The design, adjustment and therefore the characteristics of the control are largely determined by the limitations of the device.

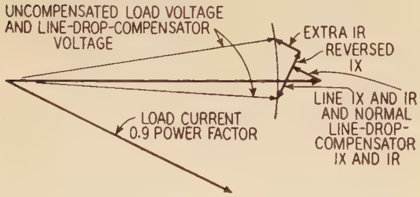
In the direct or series devices, the ratio of incoming to outgoing voltage is varied by changing the ratio of $\phi_1 N_1/\phi_2 N_2$. This is accomplished by changing the turn ratio N_1/N_2 in the case of step regulators and load-ratio-control transformers or by changing the flux ratio ϕ_1/ϕ_2 in the case of induction regulators.

The induction regulator is controlled by the same voltage-regulating relay as a load-ratio-control transformer but its response is instantaneous rather than delayed because of the fact that it can stand the duty of making frequent voltage corrections.

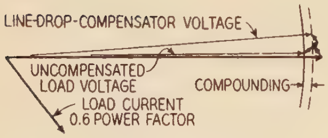
The characteristics of the regulated

voltage and therefore of the device itself are determined by the setting of the voltage-regulating relay and the line-drop compensator. The voltage-regulating relay is sensitive and responds to changes in voltages of only a fraction of a per cent. To take full advantage, as far as regulated voltage is concerned, of the sensitivity of the voltage-regulating relay would result in almost continuous operation of the induction regulator due to the continual variation in the incoming supply of voltage. It has been found practical to adjust the voltage-regulating relay used with induction regulators to initiate corrections when the voltage variation exceeds one per cent from the desired level. This constitutes a total band width of two per cent. Corrections would be small and very frequent except for the fact that the voltage-regulating relay is equipped with holding coils which, when the correction is initiated, hold the contacts closed until the voltage is corrected to approximately the center of the band. This holding adjustment of the voltage-regulating relay for induction-regulator control differs from that for step regulators in that with step regulators only sufficient holding is used to insure successful contact operation.

The induction regulator responds immediately when the control initiates a voltage correction, with the result that, except for instantaneous fluctuations, the regulated voltage is kept within the band setting. This is an important characteristic of induction regulators and should be evaluated on the basis that any decrease in variation of regulated voltage permits an increase in the allowable drop in the load area for certain given maximum and minimum voltages on customers' premises.


UNCOMPENSATED LOAD VOLTAGE AND LINE-DROP-COMPENSATOR VOLTAGE
EXTRA IR
REVERSED IX
LINE IX AND IR AND NORMAL LINE-DROP-COMPENSATOR IX AND IR
LOAD CURRENT 0.9 POWER FACTOR

A—FULL LOAD


LINE-DROP-COMPENSATOR VOLTAGE
UNCOMPENSATED LOAD VOLTAGE
COMPOUNDING
LOAD CURRENT 0.6 POWER FACTOR

B—LIGHT LOAD

Figure 2. Reducing or even reversing the reactance compensation is an effective method of stabilizing regulators operating in parallel where reactance constitutes a large part of the impedance of the circulating path and the circulating current is therefore largely reactive. Increasing the resistance setting to offset the reduced reactance setting will have a compounding effect as shown if the power factor is higher at full load

Single-phase induction regulators are basically different from three-phase induction regulators in the manner of varying voltage. In the single-phase induction regulator the voltage induced in the series winding varies from a maximum value to zero and is always in phase with the excitation of the shunt winding. The fact that no voltage is induced in the series winding of a regulator at a certain position of the rotor makes it possible to by-pass the series winding when switching the regulator in or out of service. The fact that the induced voltage is in phase makes parallel operation feasible. The three-phase regulator, on the other hand, varies voltage by changing the phase of a constant series voltage through 180 degrees. By-passing three-phase regulators requires paralleling with another similar three-phase regulator set in the same relative position, or the use of impedance to limit the circulating current when the series winding is short circuited. Except in the maximum raise or lower position, the three-phase induction regulator displaces the phase of the regulated voltage and parallel operation requires the use of some means for keeping the rotors of the regulators in the same relative position. This has been accomplished by mechanical connection or by the use of Selsyns.

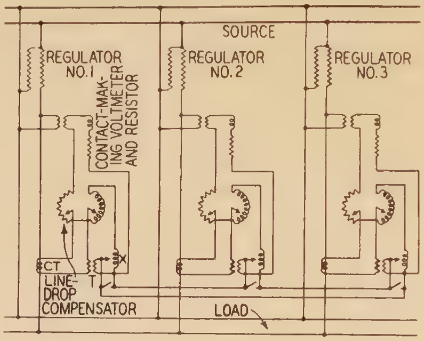


Figure 3. The use of paralleling reactors (X) inserted in the contact-making voltmeter circuits by means of insulating transformers (T) is an effective method of paralleling regulators in the same station. This scheme also requires a low-power-factor circulating current for successful operation, but it has the advantage of permitting the line-drop compensator settings to match the characteristics of the feeder circuit

One method of eliminating phase displacement in three-phase regulators that is used occasionally is the interconnection of two three-phase regulators in such a way that the phase displacement of one is compensated for by an equal and opposite phase displacement in the other.

It is inherent in the design of the induction regulator to have a lower as well as a raise range. Full use can be made of the total lower and raise range by properly selecting the substation bus voltage with the aid of transformer taps or by the use of a fixed boost in the feeder circuit as shown by *B* and *C*, figure 1. The installation of shunt capacitors for power-factor correction produces a voltage rise in the feeder circuit as shown by figure 1 *C*, and like a fixed boost enables the full use of the lower and raise range of the regulator without raising the substation bus voltage, providing the voltage rise produced by the capacitor equals the lower range of the regulator.

Branch-Feeder Induction Regulator (4)

The small single-phase induction regulator (12 and 24 kva, 2,400 and 4,800 volts) especially designed for pole mounting has the same general characteristics as the station-type induction regulator. Utilizing the same control, it is capable of the same precise voltage regulation. This characteristic makes it suitable for use on main circuits serving important loads. Being designed to supplement the station induction regulator on long heavily loaded branches or to compensate for voltage drop in the load area, the branch-feeder induction regulator operates more slowly than the station regulator. In case of simultaneous operation, the station regulator will make its corrections very rapidly in comparison to the branch induction regulator and eliminate any unnecessary operation on the part of the latter.

The operation of the branch induction regulator is sufficiently slow to permit the omission of the brake. This important simplification points to low maintenance requirements, which is an important characteristic of the device.

Regulating Transformers (5) and Station-Type Step Regulators (6)

The characteristics of a regulating transformer are identical with those of a load-ratio-control transformer as far as correction of voltage is concerned. It is a question of transformer design as to whether load-ratio-control features should be provided in the power transformer used for producing the major change in voltage levels, or, alternatively, to build the main transformer as a fixed-

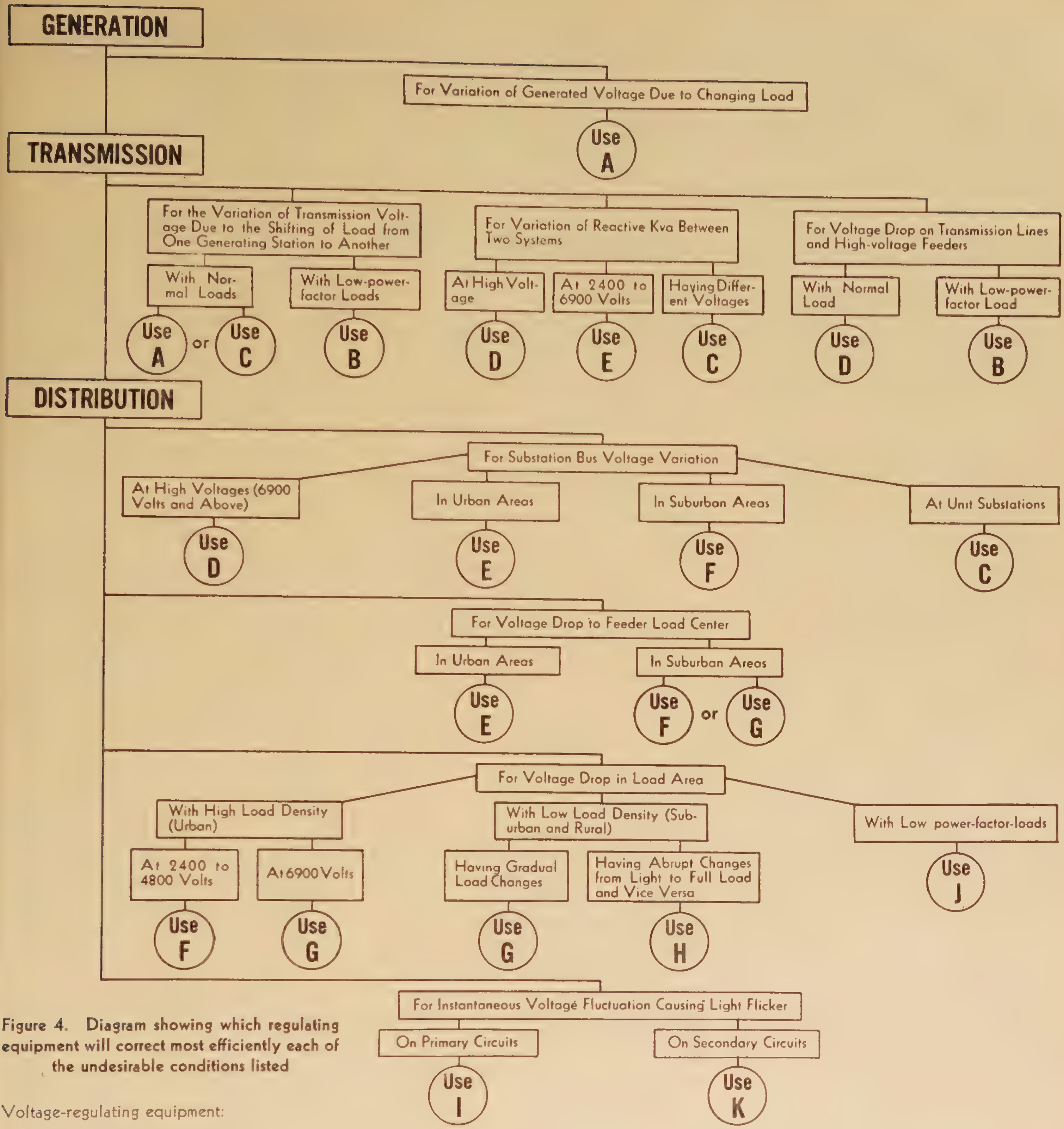

GENERATION
For Variation of Generated Voltage Due to Changing Load
Use A
TRANSMISSION
For the Variation of Transmission Voltage Due to the Shifting of Load from One Generating Station to Another
With Normal Loads
Use A or Use C
With Low-power-factor Loads
Use B
For Variation of Reactive Kva Between Two Systems
At High Voltage
Use D
At 2400 to 6900 Volts
Use E
Having Different Voltages
Use C
For Voltage Drop on Transmission Lines and High-voltage Feeders
With Normal Load
Use D
With Low-power-factor Load
Use B
DISTRIBUTION
For Substation Bus Voltage Variation
At High Voltages (6900 Volts and Above)
Use D
In Urban Areas
Use E
In Suburban Areas
Use F
At Unit Substations
Use C
For Voltage Drop to Feeder Load Center
In Urban Areas
Use E
In Suburban Areas
Use F or Use G
For Voltage Drop in Load Area
With High Load Density (Urban)
At 2400 to 4800 Volts
Use F
At 6900 Volts
Use G
With Low Load Density (Suburban and Rural)
Having Gradual Load Changes
Use G
Having Abrupt Changes from Light to Full Load and Vice Versa
Use H
With Low power-factor-loads
Use J
For Instantaneous Voltage Fluctuation Causing Light Flicker
On Primary Circuits
Use I
On Secondary Circuits
Use K

Figure 4. Diagram showing which regulating equipment will correct most efficiently each of the undesirable conditions listed

Voltage-regulating equipment:

A—Generator voltage regulators
B—Synchronous condensers
C—Transformers with tap changing under load
D—Station-type step regulators
E—Station-type induction regulators
F—Branch-feeder induction regulators
G—Branch-feeder step regulators
H—Branch-feeder boosters
I—Series capacitor
J—Shunt capacitor
K—Autotransformer

ratio transformer, all regulating to be performed by load-ratio-control equipment in a regulating transformer. The latter type of transformer is also applicable where there is no question of any major change in voltage level but where a variable voltage ratio between two circuits of the same nominal voltage is desired for voltage regulating purposes. Changing the voltage ratio of the regulating transformer and the station-type step regulator, as previously pointed out, is accomplished by changing the turn ratio. This, of course, involves a switching operation of the tap-changing mechanism. Recognizing contact wear and mechanism life as functions of the number of operations, all manufacturers of step-type regulators recommend delayed response to reduce the number of operations and so obtain reasonable maintenance expense. Increasing the band width of the control likewise reduces the number of operations. Either of these expedients to reduce the number of operations results in increasing the variation of regulated voltage.

In the regulation of higher-voltage circuits (6,900 volts and up) the lower cost of the step-type regulator usually is more important than the closer regulation obtainable with induction-type equipment. In addition to this, the voltage variation caused by the fluctuation of a given load will decrease as the voltage increases, and so operating requirements are less severe on subtransmission circuits than in the case of lower-voltage distribution feeders.

The conventional step-regulator produces an in-phase voltage correction, in contrast to the three-phase induction regulator. From this standpoint the step-regulator is especially suitable for regulating high-voltage feeders supplying low-voltage networks. The paralleling of several step-regulated feeders serving a low-voltage or a medium-voltage network smooths out the load voltage because of the circulation of equalizing currents and so results in a smaller variation of regulated voltage than would obtain on a radial feeder whose voltage is controlled by a similar step regulator.

The power factor of circulating current depends on the ratio of resistance to reactance in the loop in which it flows. The magnitude of the circulating current is determined by the magnitude of the voltage difference which produces it. With proper adjustments of the control—that is, of the voltage-regulating relay and line-drop compensator—stable operation (of the several parallel regulated feeders) can usually be obtained. Stability can be readily checked by comparing on the same base, the voltage drop of the circulating current in the loop beyond the regulating device with twice the voltage drop or rise in the line-drop compensator resulting from the circulating current. If the in-phase voltage required to circulate the current is not much more than twice that caused by the circulating current in the line-drop compensator, there is a possibility of instability. The factor 2 appears, of course, because of the fact that in the case of two parallel feeders, the circulating current has an outgoing and return path and as only one feeder constitutes the outgoing path and only one the return path, the circulating current would affect only two line-drop compensators. Obviously the greater the uncompensated impedance in the circulating path, the more stable will be the operation.

In cases where stable operation is difficult to obtain, several possible expedients may be considered. The simplest of these is to decrease or reverse the reactance element in the line-drop compensator. This is effective where reactance constitutes a large part of the impedance of the circulating path and the circulating current is therefore largely reactive. Decreasing or reversing the reactance compensation (with the corresponding increase in resistance compensation to give the desired load-center voltage at full load) results in a compounding effect as the load increases, providing, of course, that the power factor also increases with the increase in load. This is shown by vector diagrams *A* and *B* in figure 2.

Where regulators of paralleled feeders are located in the same station, paralleling reactors, such as shown in figure 3, can occasionally be used to advantage. This scheme requires the insertion of a reactance in the current transformer secondary circuit by means of an insulating transformer in addition to the ordinary connections of the voltage-regulating relay. In operation the reactive element of the circulating current produces drops in the paralleling reactors which by their effect on the voltage-regulating relay tend to hold the regulators together. Auxiliary switches are used to short-circuit the reactor of any regulator not in service. This scheme also utilizes the reactive component of circulating current, but it has the advantage of permitting line-drop compensator settings in accordance with the characteristics of the feeder circuits.

The step regulator with conventional control and line-drop compensator set to hold voltage at a given point on the circuit will hold voltage at that point regardless of the direction of power flow so long as the requirements for voltage correction do not exceed the range of the regulator. The most frequent situation involving reversal of power is that of a small load and a generating plant tied into a larger system. In such a set-up it is usually desired to hold voltage at the load regardless of power flow and the regulator would therefore be installed between the load and the larger system and the control arranged to hold voltage on the load side of the regulator.

It is rarely necessary to provide for changing control from one side of a regulator to the other. This is required only when the reversal of power is caused by a complete reversal of the principal load and the principal source of power. In installations of this type the voltage-regulating relay is usually switched from one line-drop compensator to another so that different settings may be used for the two different operating arrangements.

Branch-Feeder Step Regulator (7)

There is but little justification for installing a device having operating characteristics which excel the inherent voltage characteristics of the circuit on which it is applied. In other words, the practical advantage of installing a device capable of making fine adjustments in voltage on a "shoe string" circuit subject to large sudden fluctuations in voltage is negligible.

The branch-feeder step regulator is a supplementary regulating device whose operating characteristics correspond to the voltage characteristics of the type of circuit on which it is intended to be installed. This regulator covers a range of 10 per cent in four $2^1/_2$ per cent steps. This 10 per cent range can be allocated by means of an easily accessible terminal board to give any combination of raise and lower within the total range of 10 per cent; that is, it can be connected for 10 per cent raise, $7^1/_2$ per cent raise and $2^1/_2$ per cent lower, 5 per cent raise and lower, $2^1/_2$ per cent raise and $7^1/_2$ per cent lower, and finally 10 per cent lower. This regulator is controlled by the same sensitive voltage-regulating relay used on the induction and step-type regulators which with the $2^1/_2$ per cent step and the inherent time delay of the mechanism combine to keep the number of operations of the device and the resultant maintenance at a minimum.

Branch-Feeder Booster (8)

The one-step regulator has voltage-sensitive control and is designed to boost the voltage automatically at infrequent intervals to take care of periodic heavy demands on an otherwise lightly loaded circuit. By means of terminal board connections, the amount of automatic boost can be varied from $2^1/_2$ to 10 per cent. The series winding is tapped in four $2^1/_2$ per cent sections which can be connected to give a continuous boost in addition to the automatic boost as long as the continuous plus the automatic boost does not exceed 10 per cent. Also, the winding can be connected to lower instead of raise the voltage or to provide any combination of continuous raise or lower plus an automatic raise or lower within the range of the series winding.

A one-step device allows the use of a two-position control instead of the three-position voltage-regulating relay (raise, lower, and balanced) required for multi-step regulators. The single-step booster uses a simple resonant relay as the voltage-sensitive element. The basis of this relay is a nonlinear circuit consisting of a resistor, a reactor, and a capacitor connected in series with an auxiliary relay coil connected across the capacitor. The nonlinear characteristics of the circuit permit an accurate and permanent adjustment of the pick-up and drop-out of the auxiliary relay.

Synchronous Condenser With Voltage Regulator (9)

The chief application of this means of regulating the voltage is to situations requiring power-factor correction. Such correction, in the case of transmission systems, may involve under-excited operation of the synchronous condenser. Modern types of generator voltage regulators are available for providing continuous automatic control of the excitation of the condenser throughout its leading and lagging range. Obviously, such equipment is suitable for rapidly correcting deviations from the required voltage level.

Shunt Capacitors Controlled by a Voltage-Regulating Relay (10)

Automatically switched shunt capacitors have found limited application in Europe[8] as a substitute for the voltage-regulator-controlled synchronous condenser where the absence of rotating machinery with the associated maintenance and control problem, as well as the losses involved, have favored this solution. This scheme is in general limited to adjusting the amount of connected capacity in a few steps and because of the duty on the switchgear involved the scheme is not well adapted to rapid and frequent correction of voltage conditions. In case of loss of load, further switching problems arise which have apparently been successfully solved in Europe only because of the longer switching times that are considered satisfactory there as compared with American practice.

The recent introduction in the United States of a low-capacity low-cost equipment to switch shunt capacitors installed on feeder circuits has opened a new field for this method of voltage control.

In some instances the voltage rise imparted to a circuit by a shunt capacitor, installed for power-factor correction, exceeds desirable limits under light load conditions. This objectionable feature can be eliminated by disconnecting all or part of the capacitors with this automatic switch. A conventional voltage-regulating relay controls the switch which has sufficient inherent time delay to prevent unnecessary switching of the capacitors with momentary transient voltage fluctuations.

If more than one step is desired, a corresponding number of these switches, all controlled by the same voltage-regulating relay, can be used. The use of a multistep equipment located at the extremity of a feeder circuit provides an effective means for compensating for more or less voltage drop throughout the entire load cycle.

Shunt Reactors Controlled by a Voltage-Regulating Relay (11)

The use of such reactors has been proposed, especially where the charging current of high-voltage transmission lines would otherwise require the connection of synchronous condensers having excessive lagging capacity. However, this scheme is subject to some of the same disadvantages as the use of shunt capacitors controlled automatically in blocks and has the further disadvantage of being useless if correction of low power factor is required.

Shunt Reactors With Saturating Windings Automatically Controlled (12)

Although not subject to the disadvantage of changing the voltage in large steps as is the case when shunt reactors are switched in and out of circuit, shunt reactors having saturating windings are limited to locations where correction of low power factor will not be required and also cannot be used to correct lighting flicker conditions, since the time constant of the d-c saturating circuit precludes instantaneous response to voltage changes. Furthermore, unless special construction is used, it is not possible to eliminate objectionable harmonics, due to the presence of high saturation in the reactor core, that will introduce new problems from the standpoint of inductive coordination. Most of the special construction features used or proposed to eliminate such harmonics are definitely limited to certain system connections not usually encountered in the United States.

Series Capacitors (13)

When used to correct voltage conditions, it must be realized that at best, series capacitors cannot correct for variations in the supply voltage of the circuit but can only correct for the inductive voltage drop. To be effective at all, the ratio of reactance to resistance in the circuit must be high, and care must be used in their application to circuits to which certain types of load are connected.[9] Series capacitors are relatively expensive because they must be entirely at line potential and also include special protective means for short-circuit conditions on the feeder or transmission circuit to which they are applied. In general, it will not be found advisable to attempt to over-compensate for the reactance drop in an attempt to correct for part of the resistance drop in the circuit. The existence of tapped loads along the feeder will frequently make it inadvisable to consider their application. Although unsuited for correcting light flicker due to sudden loads at high power factor, they offer probably the most effective single corrective means for rapid voltage fluctuation due to low-power-factor load increments.

Series Reactor With Saturating Windings (14)

Although the freedom from moving parts and absence of need for special short-circuit protection for the reactor itself at one time made this device look promising for feeder-regulating purposes, it has not as yet found general application. It necessarily has a bad effect on the circuit power factor, and is too slow in action to mitigate light flicker appreciably.

Summary

As an example of how the commoner types of voltage-regulating equipment may be applied to a power system primarily on the basis of their characteristics, figure 4 has been prepared.

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A D-C Transformer

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THE COMPANY with which the authors are connected undertook the design and construction of a device using a mechanical commutator which would transform direct current from one voltage to another.

The two major commutator problems are current collection and commutation. It is well known that it is difficult to solve these problems especially if certain limits are exceeded. In the case of current collections, the speed of moving contacts cannot be indefinitely increased.

In the case of commutation the chief limitation is in the voltage per bar. Designers of commutator machines have established limits of a few hundred volts in the case of small current and limits of about 60 volts for machines of any considerable output. To obtain practical designs of commutators for high-voltage circuits it is necessary to increase the voltage per bar to very large values, usually approaching the breakdown voltage of the air or other medium surrounding the bar. As sparking may ionize the air and initiate arc-over, it is necessary to have very nearly perfect commutation and current collection.

Accepting this requirement of design, it is necessary to devise circuits which will give very good commutation of current and voltage under all conditions of service. Such circuits may be arranged to rectify or invert alternating or direct current or to transform direct current from one voltage to another. If rectification or inversion is attempted, two great difficulties are encountered. First, that of obtaining perfect synchronization of the commutator with the alternating potential and, second, the balancing of the current and voltages of the a-c system against those of the d-c system. If the currents from any finite number of phases of alternating current are rectified and totaled, the resultant current is pulsating and consequently will not perfectly balance a continuous current.

These difficulties are absent in the case of transformation of direct current, using two commutators carried on one shaft and connected respectively to the primary and secondary of a suitable transformer. Synchronization is perfect and inherent and if the number of commutator bars per circuit is the same on the primary and secondary sides of the apparatus, a true balance of current and voltage is possible. The work described in this paper was based on this type of apparatus.

In the course of the experiments, many types of commutators and circuits were tested, the earlier tests resulted in the arrangement shown in the circuit diagram of figure 1. Typical oscillograms are shown in figure 2. Figure 3 is a photograph of the test arrangment.

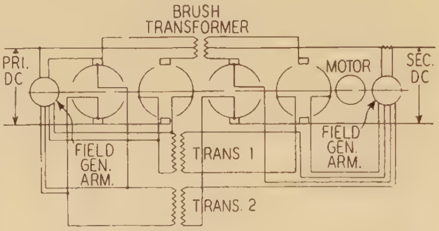

Figure 1. D-c transformer circuit with synchronous excitation and commutation and with brush transformer

This circuit employs synchronous condensers to supply the transformer excitation and to commutate the load current. This earlier work covered a period from 1924 to 1926. At that time we were not aware of any work having been done with this type of circuit. Subsequently a patent[1] came to our attention. Within the last few years the work of others[2] on this same type of circuit has been published. Since these publications explain the principle of operation we need discuss only the brush transformer which is a novel feature and not included in other circuits.

The most desirable wave shape of transformer voltage, from the standpoint of the commutator, is a trapezoidal shape. This would ordinarily necessitate a special and difficult design of synchronous condenser to supply the excitation, but, by adding the brush transformer to the circuit, a standard sine-wave generator may be used, as the brush transformer absorbs the difference between the supplied and the required voltage wave shapes.

Since the apparatus is essentially a transformer, it was felt that the measure of its success would be its ability to meet the same tests as a normal power transformer which includes short circuit, sudden application and removal of voltage with and without load, double-voltage test, etc.

The apparatus shown in figure 2 was operated at loads up to approximately 30 kw, 1,300 volts for periods up to 12 hours. Nevertheless, it was concluded that this type of apparatus could not be made to successfully withstand the tests specified above for the following reasons:

(1) It is extremely difficult, and one might say practically impossible from a practical and economical standpoint, to design synchronous condensers of any appreciable size that would respond fast enough to prevent flashing over the apparatus on sudden large voltage or current changes.

(2) In the type of commutator (open-circuit type) required, the brush rides alternately on conducting and insulating segments. Because of the difference in the material of the segments, unequal wear results, producing sparking and ultimate failure. Also the insulating segments become dirty and necessitate providing very long creepage paths. To minimize these troubles, very frequent servicing of the commutator would be required.

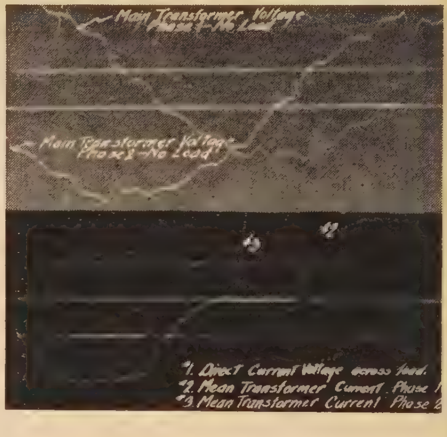

Figure 2. Wave forms obtained with circuit of figure 1

(3) The difficulties outlined above and other difficulties, such as minute sparking, that are negligible at small currents and voltages are greatly magnified at higher currents and voltages and cause frequent flashover.

Further experiments to find a more satisfactory circuit resulted finally in the circuit shown in figure 4 and photograph,

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[1] For all numbered references, see list at end of paper.

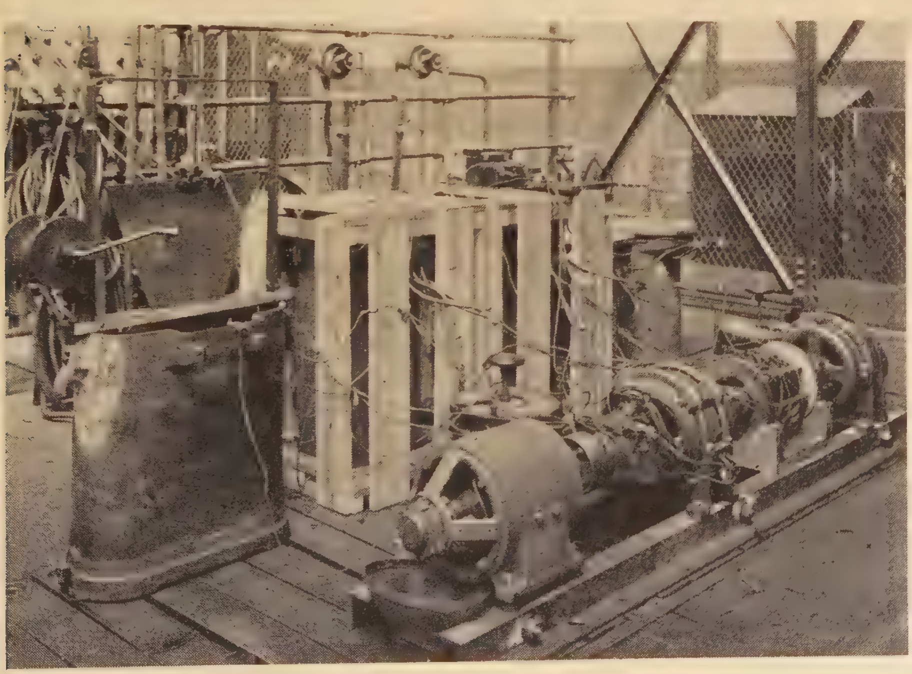
figure 5. In this circuit static condensers are substituted for synchronous condensers, the brush transformer is eliminated and the commutator is changed to the type (short circuit) in which the brushes ride solely on conducting segments with an air gap as insulation between the segments.

Most of the subsequent tests were made with the circuit shown in figure 4. A large number of tests were made at loads of 100 to 200 kw, 3,000 volts direct current. Since the only previous disclosure of this apparatus has been by patent,[3] it will be discussed in detail.

Referring to figures 4 and 5, there are seen to be two commutators mounted on a driving shaft with a motor. A minimum of six bars per commutator, connected through suitable slip rings to the primary and secondary windings, respectively, of a three-phase transformer are required. For mechanical reasons, a larger number of commutator bars, which must be a multiple of six, is desirable. The commutators shown in photograph, figure 5, have 18 bars, of which three are connected to each slip ring.

The transformer is of normal construction with reactance and losses such as are acceptable for commercial a-c use. Lower core density than usual was used, for reasons to be explained later. The frequency depends on the rotational speed of the commutator and may consequently be selected to suit the particular design.

Figure 3. Apparatus used for tests of circuit of figure 1



The motor has a suitable regulating device to enable it to maintain constant speed under all conditions.

Voltage Commutation

Three excitation capacitors are connected diametrically on the six-phase primary winding of the transformer. They may equally well be connected to the secondary as the magnetizing ampere-turns may be supplied through either winding.

Assume that the commutators are rotated at constant speed, that d-c voltage is applied to the brushes of the primary commutator and that the three-phase transformer is of core-type construction. The voltage generated in each phase will be of the form shown in figure 6, provided the correct size of excitation capacitors are used and provided the timing of the commutator as determined by brush width, bar width, and slot width is correct.

To explain the generation of the voltage, reference should be made to the simplified diagram of figure 7*a*. As the commutator revolves the two active bars come under the brushes and full d-c voltage is applied to the winding and capacitor. This continues for the period 1-2 in figure 7*b*. The d-c line is then disconnected by the commutator until connected in the opposite direction for the period 3-4.

When the connection is made at 1, sufficient current will flow into the capacitor to charge it up to the potential of the d-c lines. At the same time current will begin to flow through the winding and will increase at such a rate as to generate a counter electromotive force in the winding equal to the d-c line voltage in accordance with equation:

$$e = L\frac{di}{dt}$$

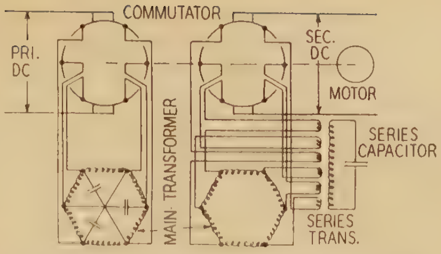


Figure 4. D-c transformer circuit with static-capacitor excitation and commutation

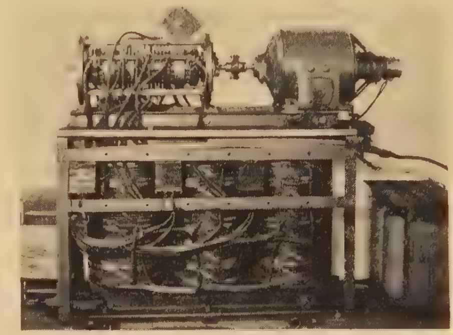


Figure 5. Apparatus used for tests of circuit figure 4

When point 2 is reached and the coil and capacitor are disconnected from the line, this current in the coil will be forced to flow through the capacitor. The result is that the capacitor is rapidly discharged and an oscillatory current set up in the loop formed by the coil and capacitor. The resultant oscillatory voltage across the coil and capacitor will have the form shown at E_1 in figure 7*b*. It will oscillate until the commutator reconnects the d-c line at 3, when it will be absorbed by the line, and d-c voltage applied to the coil in the opposite direction.

The frequency and amplitude of the oscillatory voltage are determined by the relative inductance, resistance, and capacitance of the circuit. These factors are under the control of the designer, as are the relative periods of time 1-2 and 2-3. Consequently, by varying these constants, and more particularly, by selecting the correct capacitor for a given transformer, the oscillation may be made to take the form E_2 of figure 7*b*. Here the crest of the first half cycle of the oscillation coincides in time and magnitude with the d-c line voltage which is applied to the coil at 3. The result is a smooth commutation of the voltage of the coil during the time it is disconnected from the line, and, an alternating voltage in the coil of the form E_2. The capacitor being directly connected to the coil offers a circuit of negligible reactance, so that the coil current may be diverted at 2 from the d-c line to the capacitor without causing a spark. At 3 the coil and capacitor have a voltage equal to line voltage and are consequently reconnected without sparking.

In the case of the six-phase system the interaction of three phases results in the voltages shown in figure 6. The lower trace of the oscillogram, figure 8, shows such a wave form of voltage.

It will be noted that commutation of the voltage is obtained by matching the frequency of an oscillation with the speed of a commutator. Obviously, in order to maintain this condition the speed of the commutator must remain constant. Moreover the inductance and capacitance of the circuit must also be constant, as otherwise the frequency of oscillation will change. This precludes the use of transformer core densities approaching saturation, as a small change in applied voltage will result in a great change in inductance in such a transformer. The iron should be worked at appreciably lower densities than those customary in power transformers. This necessitates a reasonably high frequency if economical design is to result, and that in turn requires high commutator speeds—this being one of the difficulties of the design of such apparatus. The commutation of rapidly changing voltages offers other problems which will be described later, together with their solution.

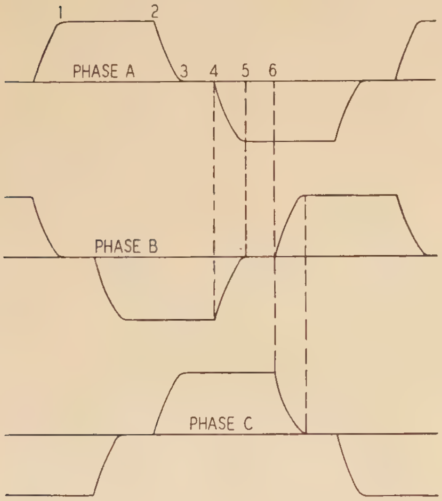


Figure 6. Phase voltages obtained with circuit of figure 4

Load Commutation

Now assume that a load is connected to the secondary terminals of the circuit shown in figure 4. Direct current will flow from the brushes to the load and must pass through the transformer windings. Corresponding currents will flow in the primary windings and will be drawn from the primary d-c line.

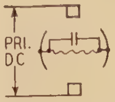


Figure 7a (left). Schematic diagram of excitation of circuit

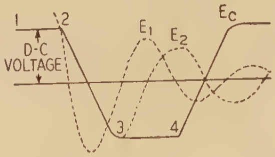


Figure 7b (right). Wave form of voltages

The wave form of current in the transformer winding will be as shown in figure 9. During the period when the brushes are not short-circuiting any bars, all phases will be in series on each side of the polygon and $^1/_2$ d-c load current will flow through each of them. This condition exists during period 2-3, figure 9. The currents in the secondary commutator (figure 4) must also pass through the windings of the single-phase series transformer and a corresponding current will be induced in its secondary winding. This current will charge the series capacitor and raise the potential across its terminals. It may be noted that all the currents in the primary windings of the series transformer are not additive, four being in one direction and two reversed, the algebraic sum being effective in inducing current in the secondary.

At time 3, figure 9, the commutator will have moved so that two bars of phase 1 are simultaneously under each brush and both windings of one phase of the transformer are short-circuited. Also, these short circuits each include two windings of the series transformer. The voltage of the charged series capacitor is, therefore, available to circulate current in the loop formed. At the moment the short circuit is caused by the brush, one-half d-c line current is flowing in each winding. The current set up by the capacitor voltage tends to decrease this current. Due to the leakage reactance of the transformer windings in which the current is flowing, the current not only decreases to zero but passes through zero and tends to oscillate at a frequency determined by the constants of the circuit. By suitably designing the commutator and transformers and selecting the correct capacitance, this oscillation is made such as to cause the current, at approximately the crest of the first half wave, to coincide in time with the clearing of the short circuit by the further rotation of the commutator and in value with one-half of the d-c line current. The result is that current is diverted to the d-c line without sparking. The dash curve C_1, shown for phase 2, figure 9 indicates in more detail the nature of this commutation of load current.

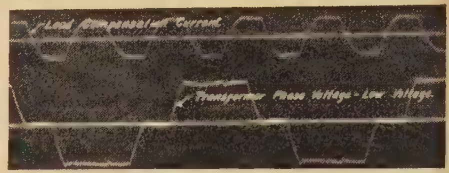


Figure 8. Oscillograms of commutation current and phase voltage of circuit of figure 4

The current in the series transformer secondary and in the capacitor is shown in the top trace of figure 9. It is seen to be the algebraic sum of the three-phase currents and to be of triple frequency. The top trace of the oscillogram, figure 8, shows this current.

As in the case of voltage commutation previously described, the success of the scheme depends on the maintenance of a fixed frequency and of fixed constants in the circuit.

The commutating circuit forms a closed loop during the commutating period and commutation proceeds independently of occurrences in other parts of the apparatus, giving a final value of current exactly equal and opposite to the initial value. Consequently, if the d-c line current changes during this period due to changes in load, the final current will not be equal to the new value of the d-c current and arcing at the brushes will occur. This is the primary cause of difficulty in commutating during load transients and short circuits. The means used to mitigate these difficulties will be discussed later.

The charging of the capacitor during the period between commutations is necessary to store up sufficient energy to supply the resistance losses of the circuit during commutation. Too short a charging period for the capacitor will result in the current failing to reach the correct value at the correct time, regardless of the value of the capacitance provided.

As a result and as may be seen from C_1, figure 9, commutation of the current begins at a definite rate, as indicated by a tangent to the oscillation at this point, and an appreciable voltage exists between the brush and each approaching bar. The result is a tendency to burn the leading edges of both due to the sudden rush of current. This was found to be a real difficulty in the operation of the apparatus.

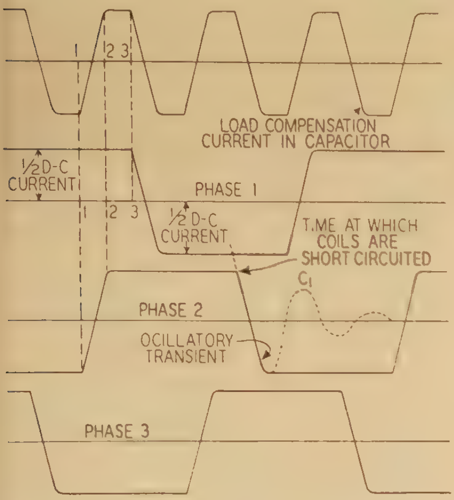


Figure 9. Current wave shapes obtained with circuit of figure 4

Commutator Design

The design of commutators intended to operate with thousands of volts between bars takes us into somewhat unexplored fields of engineering. The conventional commutator teaches little except that true roundness, and great strength and rigidity to maintain it, are of great importance. When working with high-voltage commutators it is soon found that this quality is of even greater importance and must in no way be sacrificed to insulation and other factors.

A different type of commutator from figure 5 is shown in figure 10. The largest commutator tested is shown in figure 11. Due to difficulties resulting from thermal expansion of the bars, this commutator did not operate as satisfactorily as hoped. It is of interest, however, that this commutator, together with the necessary transformers, capacitors and other parts, was used for many months as a source of 3,000 volts direct current for experiments on other models. When run under load for some hours it was observed that the leading edges of the bars and brushes would blacken no matter how much care was taken to keep the commutator smooth and round. This blackening of bars and brushes on the leading edges was due to the abrupt beginning of commutation, as previously described. The voltage of the charged series condenser causes current to flow from brush to approaching bar at a rapidly increasing rate as soon as contact is established at any point. The result is a slight spark which eats away the copper and carbon.

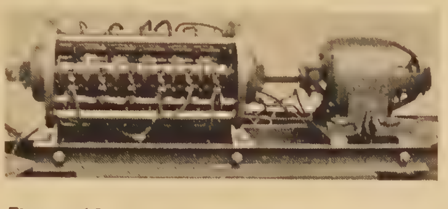


Figure 10. 100-kw 3,000-volt commutator

The commutator shown in figure 5, which was built for 25 kw, 3,000 volts was by far the most successful from the mechanical standpoint. The bars were encased in mica and clamped into deep grooves in a metal wheel. Being clamped at one point only, they could expand freely endways when heated in operation. On the heavy steel shaft is mounted a machine-steel disk. In the periphery of the disk are milled "V" shaped slots. The wedge shaped commutator bars are moulded into mica and set into these slots. The bars project from the slots on both sides of the disk. On one side were attached the slip rings and on the other the molybdenum commutator segments. Thus the whole structure was carried on the one steel disk. To obtain the necessary strength and rigidity a heavy steel retaining ring was placed over the disk and bars, and steel fillers inserted between the ring and the mica insulation on the bars. These fillers were pressed down onto the bars by set screws threaded through the ring.

The timing of the commutator is determined by the relative width of bar, of slot, and of brush. However, these factors cannot be varied outside of certain limits. For instance, a brush too narrow will not ride smoothly over the bars and slots, and slots too wide in proportion to the bar width will, similarly, lead to uneven action. As the timing is determined in part by the width of brush, it is essential that the latter be "worn in" over its whole surface and be free from broken edges.

The most unusual feature of the structure is the molybdenum segment on each bar. These were used to avoid the blackening of the leading edges of the bars. This blackening results from the voltage of commutation between brush and bar and the consequent immediate rise of current at contact. The minute spark attending this condition evidently vaporizes copper and thereby makes pittings in it. The high melting point of molybdenum, together with its slowness to oxidize prevent this to an extent within the ability of the brush to keep it polished.

However, the leading edge of carbon or graphite brushes would still blacken and get rough. In spite of the high melting and evaporating points of carbon, its poor heat conductivity, together with its readiness to oxidize, evidently caused this result. Finally a few layers of molybdenum gauze were placed against both leading and trailing faces of the brush and cemented inside a thin casing of horn fiber. The graphitized carbon of the brush was found to lubricate the molybdenum gauze sufficiently to avoid severe wear of the commutator, while the gauze resisted the destructive action of the current. With this arrangement and carefully worn in brushes many tests were run without showing any apparent deterioration of brush or bar.

Commutation With Varying Supply Voltage

Earlier tests had indicated that voltage could be thrown directly onto a "dead" machine provided it was running at normal speed, but this had never been confirmed by applying as much as 3,000 volts with a large generating capacity back of it.

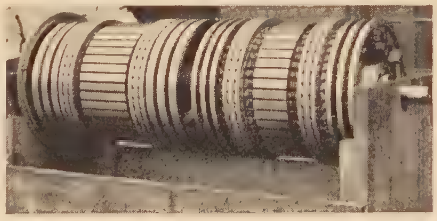


Figure 11. 300-kw 3,000-volt commutator

The principal difficulty to be anticipated here is that of commutating the transient magnetizing current that flows for a few cycles when a transformer is thrown onto the line. This transient current reaches very large values if the flux density in the iron is normally high. The low densities required for the d-c transformer, as already mentioned, bring this current down to values of the order of twice the normal magnetizing current, although the very worst condition, which is that of strong residual flux in the core and switching at the zero point of the wave, will result in somewhat more than this.

An arrangement of reactor, capacitor, and resistor, connected between the line and the commutator, when correctly proportioned, gave perfect results, no arcovers occurring during a large number of voltage applications. If load were connected to the equipment, however, the reactor core would be saturated by the d-c load current. To avoid this it was provided with two windings having the same ratio of turns as the d-c transformer, and connected in both primary and secondary d-c circuits, but in opposite directions so that the load currents opposed, and hence had no effect on the core. The d-c energizing currents flowing from either or both d-c lines do not oppose and hence encounter the full inductance of the reactor, and are effective to reduce transient voltages on the commutators. A capacitor and resistor may be connected between the reactor and commutator on the primary side only, or on both primary and secondary if the equipment is to be energized from either side. The effect is to apply the voltage gradually during the first few cycles and so reduce the transient magnetizing currents.

Commutation With Varying Load Current

By having a suitable reactor connected in series with the equipment, variations in load current will set up counter electromotive forces in the reactor which oppose the change in current and cushion the effect on the commutators. By such means the equipment is made to function satisfactorily with a varying load.

To avoid damage from flashover, the equipment may be protected with high-speed circuit breakers. There being no mechanically stored energy in the apparatus which could flow into a flashover, such protection will be much more effective than in the case of machinery with a rotating armature or field structure.

Conclusions

It is felt that the circuit constants and difficulties in mechanical construction have been fairly well explored in connection with this investigation and the data obtained should be of value in connection with new projects. The growing need of high- and low-voltage direct current in many fields of electrical engineering should result in additional applications being undertaken.

References

1. United States patent 1,206,662.

2. (*a*). SYNCHRONOUS MECHANICAL RECTIFIER-INVERTER, **S. S. Seyfert,** AIEE TRANSACTIONS, volume 52, June 1933, pages 397–407. Also AIEE *Journal,* May 1936, pages 548–53.

(*b*). NEW SYSTEMS FOR PRODUCING ELECTROMAGNETICALLY HIGH VOLTAGE DIRECT CURRENT, **E. Alm.** *Proc.* Int. Conference on Large H. T. Systems, 1935, volume 3, paper number 347.

3. United States patent 1,659,110.

Discussion

J. J. Linebaugh (General Electric Company, Schenectady, N. Y.): [**Editor's Note:** This discussion covers also "New Types of D-C Transformers," C. C. Herskind, ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), volume 56, November 1937, pages 1372–8.] It is very interesting to have the two papers describing two such radically different ways of accomplishing d-c transformation for consideration at the same time.

Engineers have long dreamed of a simple way to transform direct current from one voltage to another voltage similar to the well-known a-c transformer and numerous attempts have been made to solve this difficult problem. Most attempts have been along the lines of a commutator driven by a synchronous motor of some kind connected to operate as an inverter and as a rectifier.

The two papers on this subject—one using straight mechanical means and the other mercury-arc rectifier vacuum tubes to build up a unit which would accomplish the desired conversion—outline a very serious attempt to solve this problem so that a commercial d-c transformer would be available.

Messrs. Lenox and DeBlieux outline the line of attack followed, frank discussion of difficulties encountered, and results obtained. It is the most ambitious attempt known to the writer to solve this problem and should be of interest to many engineers and especially to any one working on the development of such a transformer in the future.

It will be of interest to know that one of the reasons for the development of the 300-kw 3,000-volt transformer was the possibility of operating standard 600-volt street cars on a standard 600-volt system and also on a 2,400- or 3,000-volt trolley system by simply throwing on and off the d-c transformer.

Several locations were considered, one being the routing of such a car from the hotel in Butte, Mont., to the hotel in Anaconda, Mont., using a 600-volt trolley in the two towns and the 2,400-volt 28-mile main line of the Butte, Anaconda & Pacific Railway between Butte and Anaconda. The scheme looked very promising, but unfortunately the automobile and good roads came along and absorbed the passenger business between the two towns.

Mr. M. A. Edwards has described a small inverter built along the lines of the unit described by Messrs. Lennox and DeBlieux using improvements and material made available since that time. This application has real merit and, if the demand for a d-c transformer becomes great enough undoubtedly the authors have opened the way to the development of a successful transformer of the nontube type.

Mr. Herskind, on the other hand, describes connections, circuits, characteristics, etc., using mercury-arc rectifier tubes to take care of commutation difficulties and sequence of circuits instead of a mechanical commutator. The circuits tried out, giving either constant current or constant voltage output, open up many possibilities for future application.

While the units under test were not as large as the 300-kw d-c transformer, they were large enough to demonstrate the practicability of such a unit.

The size of this type of d-c transformer is dependent on capacity and reliability of mercury-arc rectifier tubes.

Perhaps the d-c transformer of the future will be a combination of the two lines of attack covered by these interesting papers.

It is believed a d-c transformer can be made available for commercial use if demand is great enough to warrant the cost of development.

Transactions

Papers and Discussions Comprising Pages 559–612 of the 1938 Volume

Instruments for the New Telephone Sets

By W. C. JONES
MEMBER AIEE

Synopsis: Transmitters and receivers for use at subscribers' telephone stations have been designed which not only materially improve transmission but also simplify manufacture and facilitate maintenance. This paper discusses these improvements and describes some of the new design technique employed in their development.

As a result of continuous development work on transmitters and receivers for use at subscribers' telephone stations, new instruments have been designed which not only materially improve transmission but also embody features which simplify manufacture and facilitate maintenance. These instruments are now being produced for use in handsets, desk stands, and wall sets in the Bell System.[1]

In many respects these instruments represent outstanding advances in transmission instrument design and performance. It is the purpose of this paper to discuss these improvements and to describe some of the new design technique employed in their development. The data presented will be confined almost entirely to physical measurements which serve to define the performance characteristics of the instruments. The interpretation of these data in terms of their relationship to the characteristics of associated apparatus and their over-all reaction on transmission in the telephone plant is covered by a companion paper dealing with the transmission features of the new sets.[2]

Handset Applications

The new transmitter unit with an adapter was first introduced in 1934 as a replacement for the earlier type of handset transmitter.[3] There are now about five million of these transmitters in use in the plant of the Bell System. While experience has shown that they effect an outstanding improvement in performance they do not take full advantage of the possibilities of the unit type of construction from the standpoint of simplification, owing to the fact that a number of additional parts are required to mount the unit on the existing type of handset handle. The advantages of the unit type of instrument have been realized in a new design of handset introduced during 1937, about a million of which have been produced. This handset is shown with the new combined set in the photograph, figure 1, and in cross section on figure 2.

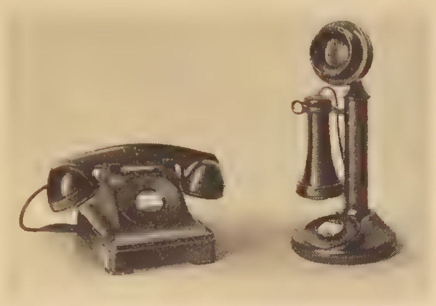


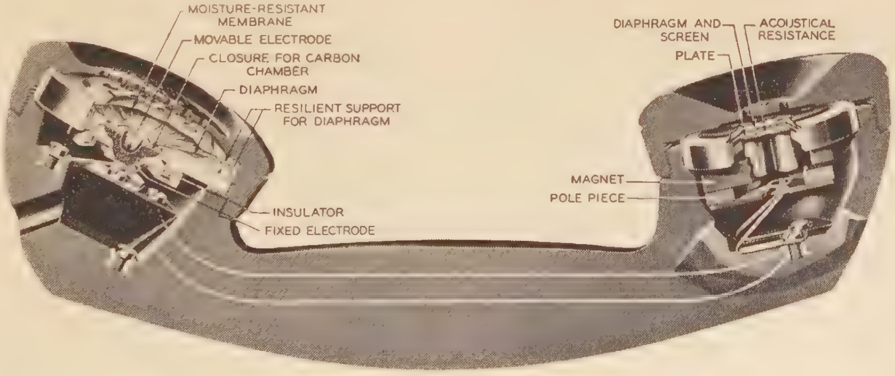
Figure 1. Handset and desk stand equipped with the new instruments

In designing this handset every effort has been made to obtain the maximum degree of simplicity consistent with the electrical requirements involved and at the same time to secure an attractive design which harmonizes with the other station apparatus on the subscriber's premises. Only three phenol plastic parts are employed; namely, the handle and the transmitter and receiver caps. In designing these parts particular attention has been paid to providing adequate cross sections at the points of maximum stress and to distributing the weight so as to reduce to a minimum the breaking moments which are developed when the handset is dropped. The transmitter and receiver caps serve the dual purpose of holding the units in place and providing mechanical protection. In addition they thoroughly insulate the user from all the metal parts which are included in the electrical circuit. Both caps have smooth surfaces which can be readily cleaned. As will be pointed out later, the grid of the receiver cap also has a transmission function and plays an important part in determining the response in the upper frequency range. Spring contacts are provided to facilitate the assembly of the units in the handle. This operation is further facilitated by the fact that specific alignment of the units and the caps relative to the handle is unnecessary. The spacing between the transmitter and receiver is such that the handset can be used with the existing type of desk mounting as well as with the new combined set.

Desk-Stand and Wall-Set Applications

The photograph, figure 1, also shows the new transmitter and receiver unit

Figure 2. Cross section of the handset



Paper number 38-81, recommended by the AIEE committee on communication and presented at the AIEE summer convention, Washington, D. C., June 20–24, 1938. Manuscript submitted April 18, 1938; made available for preprinting May 27, 1938.

W. C. Jones is transmission instruments director of the Bell Telephone Laboratories, Inc., New York, N. Y.

1. For all numbered references, see list at end of paper.

adapted to desk-stand and wall-set use. Cross sections of these instruments are shown on figure 3. The faceplate, mouthpiece, and protective grid of the transmitter are combined in one phenol plastic part which is so designed as to reduce cavity resonance to a minimum and provide response characteristics essentially the same as those of the handset transmitter. On the other hand, the mouthpiece is sufficiently prominent to encourage the user to talk directly into it and in this way reduce the losses which often result when flush-type faceplates are employed with desk-stand and wall-set instruments. A phenol plastic part, equipped with contact springs, holds the unit tightly in the faceplate and provides electrical connections.

As in the handset the unit of the receiver is held in place by the cap. Springs are provided in the shell for bringing out the electrical connections. A metal insert adds sufficient weight to meet the switch hook requirements of the existing sets. The phenol plastic parts of both the receiver and transmitter are so designed as to thoroughly insulate the units and minimize breakage.

Transmitter Unit

The new transmitter unit is of the "direct action" type, that is, one in which the movable electrode serves the dual purpose of contact and pressure surface. As is shown by figure 2, this electrode is mounted at the center of a diaphragm of thin aluminum alloy formed into a shallow cone and ribbed to add rigidity. "Books" of thin impregnated paper mounted in a recess in a die-cast frame provide a resilient support for the edge of the diaphragm. The fixed electrode is held in place in the frame by a threaded ring and is insulated from the frame by a phenol fiber washer and a ceramic insulator which also forms one of the surfaces of the carbon chamber. The active surfaces of both electrodes are gold plated. A silk annulus clamped at its outer edge between the ceramic insulator and the frame and its inner edge between the movable electrode and the diaphragm forms a resilient closure for the carbon chamber. Electrical connection between the movable electrode and the frame is provided by means of metal strips of low stiffness. Provision is made for machine filling the carbon chamber through a hole in the fixed electrode and closing this hole by means of a cap which crimps over a projecting shoulder. The exposed surfaces of the cap and the threaded ring are silver plated and form the contact surfaces for the electrical connections. A moisture-resistant membrane protects the internal parts of the unit from the effects of condensed moisture from the breath. This membrane is clamped at its outer edge between a protective grid of perforated metal and the frame. A thin metal ferrule fastens the grid to the frame. The exposed parts of the unit are anodically finished to resist corrosion.

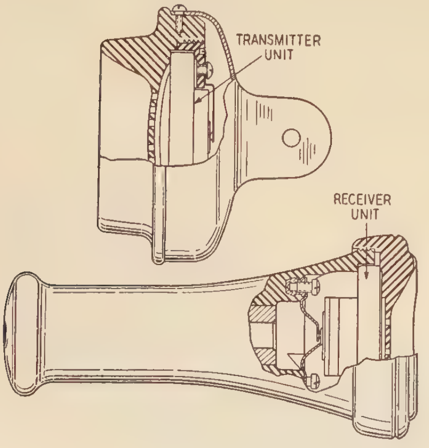


Figure 3. Cross sections of the transmitter and receiver for desk stands and wall sets

In addition to being simpler than the earlier transmitter and hence less difficult to produce, the new transmitter unit has characteristics such that:

1. Its performance is less affected by angular position.
2. There is less aging under the conditions encountered in service.
3. The electrical output is higher and the response more uniform.
4. The modulation products resulting from nonlinearity are materially reduced.

Effect of Angular Position

In order to insure good contact between the carbon granules and the diaphragm in the positions in which the handset is most likely to be held in service, the carbon chamber of the earlier transmitter was placed in front instead of the conventional location in back of the diaphragm.[3] The positional characteristics of this transmitter were further improved by the use of a "barrier" type of variable resistance element in which the electrodes are stationary and form the walls of the carbon chamber, and in which the surface of the diaphragm in contact with the granules is insulated and serves only as means for changing the contact forces between the granules in response to the variations in sound pressure at the diaphragm surface. While this transmitter represented a distinct advance in handset performance from a transmission standpoint and was quite effective in reducing undesirable positional effects, particularly in the "horizontal face-up" position, it was somewhat complicated mechanically and involved the problem of providing a closure between the diaphragm and the adjacent electrode which would be sufficiently resilient to meet the transmission requirements and at the same time prevent carbon leakage. In addition, there was some degradation in quality when it was held in the "horizontal face-down" position where the carbon granules tended to fall away from the diaphragm. While this condition occurred only infrequently in service, it was one which it was considered desirable to eliminate if this could be accomplished without making the structure mechanically complex or difficult to manufacture or maintain. A tendency also was observed in the field for the resistance to increase sufficiently under certain conditions to react adversely on the operation of the associated signaling apparatus. Owing to the inherently small areas of the sound passages leading to the diaphragm the moisture condensed from the breath could not be excluded by a membrane without complicating the structure and adding sufficient mechanical impedance to impair transmission.

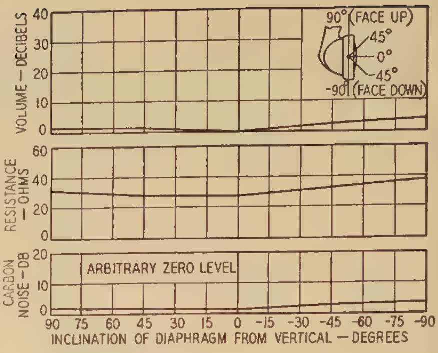


Figure 4. Positional characteristics of the transmitter

Following the introductory work on the barrier transmitter, an intensive study of the direct-action type of carbon element was made to determine whether the limitations of the earlier structures of this type, which arose from the nonfluid character of the carbon, could be overcome. This study resulted in the transmitter unit shown on figure 2. This unit eliminates the undesirable features of the inverted type without sacrificing its desirable characteristics.

The electrode surfaces of the new transmitter unit are so proportioned and so spaced relative to each other that the important current paths shift their locations in the carbon mass with changes in angular position in a manner such that the mean effective pressures in the paths and the lengths of the paths result in sub-

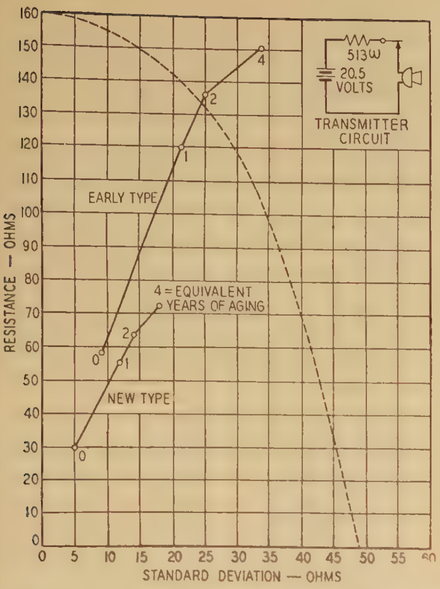


Figure 5. Limiting values of transmitter resistance

stantially constant resistance in all positions. Furthermore, the components of the axial motion of the diaphragm effective in changing the contact forces in the paths are also such as to produce essentially constant modulation. Not only is the total resistance of the paths between the electrodes substantially constant, but this resistance also is uniformly distributed between the individual contacts with the result that at no time does the contact potential rise to a value sufficiently high to produce objectionable carbon noise or "burning." These features result in resistance, volume efficiency and carbon noise characteristics which, as is shown by figure 4, are essentially independent of angular position.

Another and perhaps a more exacting criterion of the adequacy of a transmitter from the standpoint of its ability to function satisfactorily in all positions is the extent to which its transmission characteristics at normal speech intensities are adversely affected when immediately preceded by loud speech. If a poorly designed transmitter is held in a position such that the carbon granules tend to fall away from the movable electrode when this test is applied, the nonfluid action of the carbon will prevent the re-establishment of contact with the electrode surface with the result that volume losses of as much as 20 decibels and a serious degradation in quality take place. Furthermore, these losses persist until the transmitter is jarred or moved about sufficiently to change the configuration of the granules. On the other hand, if the effect of the frictional forces within the granular mass has been taken fully into account in the design of the carbon element, these forces will not react in a manner such as to prevent good contact with the electrode following the large amplitude produced by loud speech and uniform volume and good quality will obtain at all times. The new transmitter meets this test with a substantial margin.

Carbon leakage is prevented in the new instrument without impairment of transmission by the resilient silk closure for the carbon container previously mentioned.

AGING

Transmitter design has advanced to a stage where heating at the points of contact in the carbon element need no longer be an important source of aging. Therefore, such aging of the granular material as occurs in a well-designed instrument is limited almost entirely to that resulting from changes in the properties of the granules caused by abrasion of their surfaces when the transmitter is subjected to mechanical shocks such as occur when the handset is placed on the mounting. As in the case of the earlier transmitter, the new transmitter is machine filled[3] with the result that the motion of the granules and the resultant surface abrasion is reduced to a minimum.

The changes in resistance due to the residual aging have little adverse effect in so far as volume is concerned. In fact, the constants of most of the circuits in which the transmitter is used are such that an increase in resistance adds to rather than decreases the electrical output because of the greater amount of power supplied to the transmitter from the central office battery.

On the other hand, an increase in resistance, though small, may prove to be important in certain circuits where a critical relationship between transmitter resistance and the performance of associated apparatus exists. Under these conditions variations in transmitter resistance may result in failure of the associated apparatus to perform satisfactorily if certain limiting values of resistance are exceeded. In determining the limits to be placed on these values account must be taken of all the variables in the circuit in which the transmitter is connected. Obviously combinations of variables of this nature cannot be dealt with on the basis of averages alone but must include some measure of their range, such, for example, as the standard deviation.[4] The available data indicate that average transmitter resistances and standard deviations which lie within the area bounded by the dotted curve, figure 5, will have no adverse effect on circuit operation in the Bell System plant. This curve is based on certain marginal circuits of which there are a number in everyday use. An important transmitter resistance in determining the performance of associated apparatus in these circuits is the resistance during the period when the call is being established. This resistance is referred to as the signaling resistance. As is shown by the solid curves the signaling resistance of the earlier type of transmitter after artificial aging by an amount considered to be the equivalent of four years in service falls outside the acceptable area. On the other hand the resistance of the new type when aged and measured under identical conditions falls well within the limiting curve and hence not only requires less frequent replacement but also permits greater freedom in circuit design and plant layout.

Moisture condensed from the breath is an important factor in determining the life of a transmitter. A protective membrane is provided in the new transmitter unit which not only is highly moisture resistant but also results in no appreciable transmission impairment. The characteristics of the material employed in this membrane are such that it is not affected by the aging conditions encountered in service such, for example, as the alkaline reaction of water after it has been in contact with phenol plastic parts or tobacco ashes. The exposed metal parts are finished to resist the corrosive action of these agents.

RESPONSE

Reducing the transmitter to an equivalent electrical circuit provides a useful means for analyzing its performance and determining the extent to which the individual parts contribute to its response.

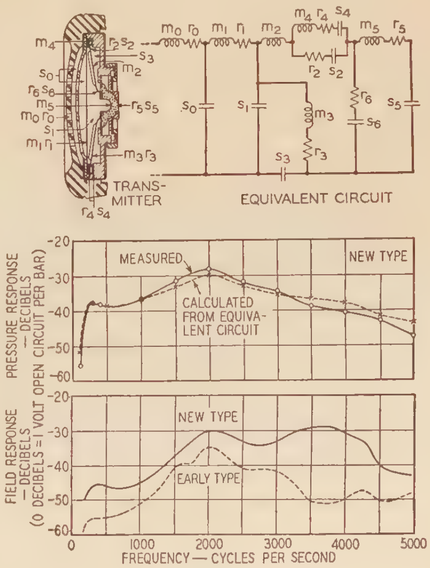


Figure 6. Pressure and field-response characteristics of the transmitter

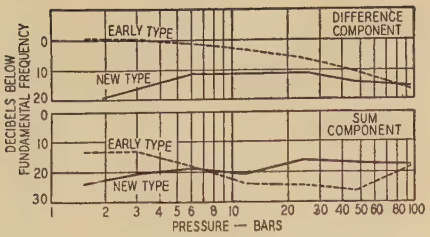


Figure 7. Sum and difference components as a function of the intensity of the fundamental frequencies

Such a circuit for the new unit is shown on figure 6.

While the diaphragm can be represented as a lumped mass for frequencies in the region below 3,500 cycles per second, it is necessary to consider it as being composed of three masses coupled by stiffnesses in order to adequately represent its performance at higher frequencies. These masses consist of the central portion m_5, the ribbed intermediate portion m_2 and the outer portion m_4. The central portion includes the mass of the movable electrode and is coupled to the ribbed portion by the stiffness s_6 which in turn is coupled to the outer portion by the stiffness s_2. The paper books which support the edge of the diaphragm have a stiffness s_4 and a resistance r_4. Their mass is included in the mass of the outer portion of the diaphragm m_4. The internal resistances of the portions which form the coupling stiffnesses s_2 and s_6 are represented by r_2 and, r_6 respectively. A hole is provided in the diaphragm to permit rapid equalization of low-frequency pressures of high intensity and prevent damage to the diaphragm and other parts. The mass and resistance of this hole m_3r_3 are so chosen that their effect on response is confined to frequencies below 300 cycles per second where the station circuit itself is relatively inefficient. The controlling stiffness s_3 is that of the cavity between the diaphragm and the die-cast frame. As is to be expected the impedance of the carbon granules is a function of amplitude and frequency. However, for the purpose of this type of analysis, their impedance characteristics can be represented to a first approximation by a constant stiffness and resistance r_5s_5. The mass of the carbon is lumped with that of the central portion of the diaphragm. The grid of the transmitter unit proper is provided for mechanical protection only and has holes large enough to have no reaction on response. When assembled in a handset or desk stand a second grid of insulating material is added. The holes of this grid have a mass and resistance, m_0r_0, which must be taken into account in arriving at an over-all picture of the factors affecting response. These holes are coupled to the moisture-resistant membrane m_1r_1, by means of the stiffness s_0 of the enclosed cavity. The cavity stiffness s_1 couples the membrance to the diaphragm.

There are two types of response-frequency measurements in general use; namely, pressure-response measurements in which a constant sound pressure is maintained at the face of the transmitter throughout the frequency range covered by the test, and field-response measurements in which a sound field of constant intensity is established at each frequency before inserting the test transmitter. Pressure response is used principally for purposes of analysis whereas field response usually affords a better measure of the performance of the transmitter under the conditions of actual use.

The pressure response of the new transmitter measured with a constant sound pressure at the grid, and the response computed from the equivalent circuit are shown on figure 6. The transmitter used in this test was artificially aged by an amount equivalent to two years of service in order to simulate more nearly plant conditions. While the computed curve departs slightly from the measured curve at certain frequencies, due to the inadequacy of some of the basic assumptions, such as those which were made relative to the impedance of the granular carbon, the agreement in general is so good as to provide a powerful tool for predetermining the response characteristics of transmitters under development and a useful method for evaluating the reaction of one element of the transmitter on another. Reducing the transmitter to an equivalent electrical circuit also has proved invaluable in determining the causes of variations in transmitter performance observed during manufacture.

As previously mentioned, the response characteristics of a transmitter under conditions of actual use may differ from those obtained with a constant pressure at its face. In general this is due to the fact that the diffraction effect of the transmitter as an obstacle in the sound field has not been taken into account. While not as readily predetermined as the pressure response, the field response can be easily measured by inserting the transmitter in a sound field of constant intensity. An artificial voice[5] is used in this measurement as a sound source and the electrical input is adjusted to maintain a constant sound pressure at the guard ring at each frequency before inserting the instrument under test. Response curves for the new and early types of transmitter obtained in this way also are shown in figure 6. Both show rising characteristics in the region of 2,000 cycles per second. While it is feasible to design a transmitter having a substantially flat field characteristic, experience has shown that the transmission obtained with a transmitter having a rising response in this frequency region more nearly approaches direct speech,[2] when used with a representative line and the new receiver, than that obtained with one having a more uniform field response.

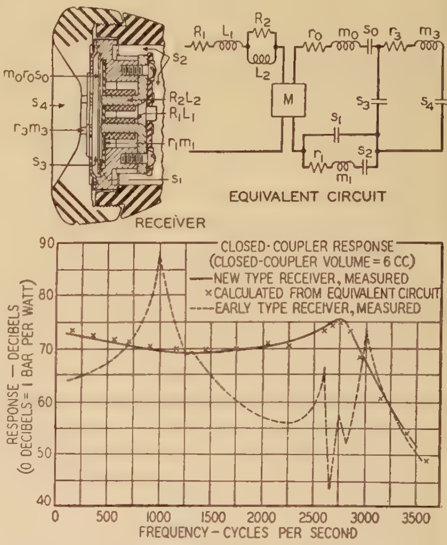

R1
L1
R2
L2
r0
m0
s0
r3
m3
s2
m0r0s0
s4
r3m3
s3
R2L2
R1L1
r1m1
s1
M
s3
s4
s1
r1
s2
m1
EQUIVALENT CIRCUIT
RECEIVER
CLOSED-COUPLER RESPONSE
(CLOSED-COUPLER VOLUME = 6 CC)
—NEW TYPE RECEIVER, MEASURED
× CALCULATED FROM EQUIVALENT CIRCUIT
---EARLY TYPE RECEIVER, MEASURED
RESPONSE — DECIBELS
(0 DECIBELS = 1 BAR PER WATT)
90
80
70
60
50
40
0
500
1000
1500
2000
2500
3000
3500
FREQUENCY – CYCLES PER SECOND

Figure 8. Closed-coupler response characteristics of the receiver

Nonlinear Distortion

A substantial reduction in nonlinearity has been effected in the new transmitter unit.

It is a well-known fact that the slope of the input-output curve of most transmitters is not unity even for sound intensities other than those at which overloading occurs. However, this departure from nonlinearity does not entirely account for the modulation products developed when two frequencies are impressed on the transmitter. Measurements of the sum and difference components in the output of the new transmitter and the earlier transmitter for frequencies of 1,500 and 1,700 cycles per second are shown on figure 7. It will be noted that whereas the difference component produced by the earlier instrument is equal to the fundamental within the speech range, the sum and difference components are both ten decibels or more below the fundamental at all the intensities measured in the case of the new unit.

A tendency for the difference component to be considerably more pronounced than the sum component in the case of the earlier transmitter is characteristic of all of the commercial instruments measured during the development of the new unit. As previously mentioned, this cannot be fully explained by a nonlinear relationship between input and output. The available data indicate that it is due to the manner in which the resistance changes cyclically when pressure waves of two frequencies are impressed simultaneously on the transmitter. Similar effects also have been observed in the microphonic action of carbon contacts themselves. Hence it is not unlikely that this is a fundamental characteristic of the carbon itself. If this proves to be true the extent to which an improvement can be effected in the performance of the transmitter will depend upon the ultimate control which can be exerted over the basic properties of the granular material.

Receiver Unit

The new receiver unit is of the bipolar permanent-magnet type. The magnetic circuit consists of pole pieces of 45 per cent Permalloy, two straight bar magnets of Remalloy and a Permendur diaphragm.[6] The magnets are welded to the pole-pieces to form a unit which is mounted on projecting lugs on the die-cast frame. The coils are wound with enamel insulated wire interleaved with cellulose acetate. The pole tips project through a phenol fiber plate which is fastened at the edge to the frame to form a cavity in back of the diaphragm. This cavity is connected to the recess in the handset handle or receiver shell by a hole in the plate. A disk of specially prepared silk covers this hole and provides the required amount of acoustical resistance. The silk fabric is so woven that it does not change in resistance with wetting and drying. The front of the unit is protected by a perforated metal grid which is assembled to the frame by means of a thin ferrule. A disk of impregnated silk is mounted between the grid and the frame to form a screen which prevents the transfer of foreign material from the front to the back of the diaphragm when the receiver is dropped. The grid and ferrule are anodically finished to resist corrosion. The spring contact surfaces are silver plated.

Prior to the introduction of this unit the receivers in general use for telephone purposes in this country and abroad employed simple resonant diaphragms and as a result had response characteristics which were characterized by prominent resonance peaks. As a rule the peak due to the first overtone, as well as that due to the fundamental resonance, fell within the important frequency range. This resonance not only introduced frequency distortion but increased the intensity with which circuit disturbances such as clicks were reproduced. Furthermore, the diaphragms of these receivers were rigidly clamped between surfaces which differed in temperature coefficients of expansion and heat capacities from those of the diaphragm with the result that the performance of the receiver was erratic and at a given time was dependent upon the temperature changes to which it had been subjected.

The new receiver is so designed that:

1. All prominent resonances within the important frequency range have been eliminated and the response within this range materially improved.

2. The effect of changes in temperature has been eliminated.

3. These improvements have been accomplished without sacrificing simplicity of design or introducing features which complicate manufacture of the receiver or increase the maintenance required.

Response

An equivalent electrical circuit for the receiver and a typical closed coupler response curve are shown on figure 8. Referring to this figure it will be noted that there are two meshes in the circuit which contain mass, stiffness and resistance and which control the motion of the diaphragm. One of these meshes consists of the acoustical resistance m_1r_1 coupled to the diaphragm $m_0s_0r_0$ by the stiffness s_1 of the cavity between the diaphragm and the plate which surrounds the pole tips. Included in this mesh is the stiffness s_2 of the cavity in the handset handle or receiver shell. The other mesh is composed of a cap grid m_3r_3 and the load s_4 coupled to the diaphragm by means of the cavity stiffness s_3. The grid of the receiver unit proper is provided for mechanical protection only and has holes large enough to have no reaction on response. The mass of the resilient screen is small and is lumped with the diaphragm mass m_0. The electrical portion of the circuit consisting of the winding R_1L_1 and the equivalent eddy current circuit R_2L_2 is coupled to the mechanical and acoustical portion by means of the force factor M.[7]

The response computed from the equivalent circuit for a number of frequencies is included on figure 8. The agreement between this curve and the measured curve is excellent and makes it possible to predetermine the response of the receiver with a high degree of accuracy, and to evaluate the effect on the over-all response of the receiver of changes in the constants of the component parts. This type of analysis also has been invaluable as an aid in establishing the causes of variations in response which have been observed during the development and production of the receiver. A measured response curve of a receiver of the earlier type has been added to figure 8 for convenience of reference. The improvement in uniformity and range of response is obvious. It will be noted that large gains have been effected for frequencies in the range from 1,500 to 3,000 cycles per second.

The response of the receiver to a square-topped wave affords an excellent measure of frequency distortion. Oscillographic records of the output of typical receivers of the new and earlier types are shown on figure 9 for a frequency of approximately 50 cycles per second. The distorting effect of diaphragm resonance is so obvious as to require no comment beyond pointing out that for accurate reproduction of square waves uniform response for an infinite frequency range is required and that the slight rounding of the corners of the wave as reproduced by the new receiver is due primarily to the falling off of its response above 3,000 cycles per second.

The substantially uniform response of the new receiver also renders clicks and other surges much less objectionable. This is due to the fact that the ear does not respond to the peak value of an oscillatory transient alone but integrates the oscillation over an interval at the beginning of the surge, hence the higher the damping the less objectionable the click.

The nonlinear distortion produced by a receiver of the new type is negligible in its reaction on transmission, the harmonics

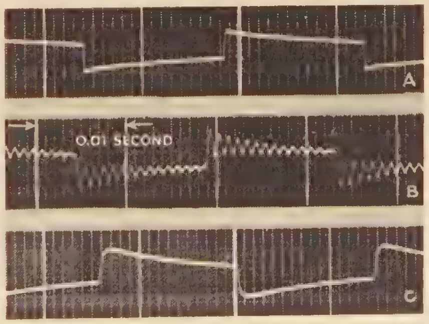


Figure 9. Response of the receiver to square waves

A—Measuring circuit—no receiver
B—Early type receiver
C—New type receiver

in the output being 35 decibels or more below the fundamental.

Magnetic Circuit

Inasmuch as the magnetic properties of the diaphragm, as well as its mechanical properties, must be considered in arriving at the preferred dimensions, it was necessary in designing the new receiver to develop criteria which could be applied in determining the optimum relationships between these factors. This study led to the use of the ratio of the force factor to the effective mass of the diaphragm for this purpose. For given magnetic materials in the pole pieces and the diaphragm and a given air-gap length, there is a pole-face area and diaphragm thickness for which this ratio is a maximum. Typical data illustrating this relationship are shown on figure 10. The available magnetic materials were studied using this technique and a decision was reached to use Permendur in the diaphragm and 45 per cent Permalloy in the pole pieces.

There is a value of polarizing flux for which the force factor of the given magnetic circuit is a maximum. The rate at which the force factor falls off above and below this optimum value of flux is a function of the magnetic characteristics of the materials employed, the length of the air gaps, etc. Without exception the more efficient magnetic circuits have been found to be the most critical as regards polarizing flux. Hence, if wide variations in the efficiency of the product receivers are to be avoided and serious losses due to subsequent demagnetization in service prevented, means must be provided not only for bringing the flux in each receiver to the optimum value, but also for insuring that it remain at this value during the life of the instrument. In order to accomplish this result the magnets of the new receiver are so designed as to overpolarize the magnetic circuit when they are fully magnetized. Equipment is provided for demagnetizing each receiver to its optimum flux value during the assembly process. Receivers which are not sufficiently overpolarized before demagnetization to resist further demagnetization under service conditions are rejected.

Temperature Effects

The diaphragm of the new receiver is held in place by the force developed by the polarizing flux and hence it is free to expand and contract independently of its seating surface. This feature renders the performance of the receiver independent of the changes in temperature to which it has been subjected. The force due to the polarizing flux is sufficiently high to prevent rattling at input intensities many times those of loud speech.

Coupling

Although station circuits can be designed which under ideal conditions result in no sidetone, this objective is never fully realized under actual plant conditions, with the result that a part of the electrical output from the transmitter always reaches the local receiver. Whether the electrical coupling between the transmitter and receiver as evidenced by the residual sidetone is of importance from the standpoint of sustained oscillation or "howling," depends upon the degree of mechanical and acoustical coupling between the instruments. Handset and instrument design has advanced to a stage where mechanical coupling need no longer be a problem. On the other hand, as the response of the instruments is improved, the acoustical coupling may become an important item in determining the howling margin. This margin is so large under the conditions where the new handset is being used for transmission purposes that there is no tendency for oscillation or distortion to occur. However, if the handset is placed face downward on a desk or table, an air column is created which resonates in the region of 2,500 cycles per second. Inasmuch as this is the region where a substantial improvement in the response of the receiver has been effected, a marked reduction in howling margin results. While there is still sufficient margin to meet all of the requirements of field use, this situation serves to emphasize the fact that such factors as acoustic coupling may limit the transmission improvements which can be effected under a given set of operating conditions.

Effective Transmission

The extent to which the better performance of the new instruments is effective in improving the grade of transmission afforded the telephone user is a complex matter and one which is influenced by such factors as the characteristics of the circuits with which the instruments are associated at a given time, the amount of noise present at the transmitting and receiving stations, the reaction of sidetone on the loudness with which the user speaks, the distance between his lips and the face of the transmitter, the tightness with which he holds the receiver to his ear, etc. Many of these factors are beyond the control of the engineer responsible for the design of the transmitter and receiver and hence can be evaluated, in so far as their reaction on transmission is concerned, only by tests made under the conditions of actual use.

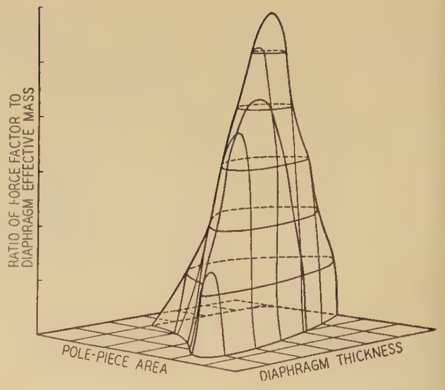


Figure 10. Force-to-mass ratio as a function of diaphragm thickness and pole-piece area

A method has been devised which makes it possible to rate the over-all effect of these factors on transmission in a way representative of the results obtained by the subscribers in their normal use of the instruments.[8] Numerous tests employing this method of rating were made during the development of the new transmitter and receiver to make certain that the course followed in their development would insure the best possible performance under service conditions. Similar tests were also made of the designs selected for production. These tests show that in many respects the new instruments represent outstanding advances in transmission instrument design and performance.

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Combined Thyratron and Tachometer Speed Control of Small Motors

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MUCH has been done in applying thyratrons to motors.[1–4] This paper is restricted to cases where the speed of the motor is measured by an electric tachometer whose output is used to control the motor input. Since this control is made fast by the use of thyratrons, it is possible to hold the speed of the motor constant under difficult conditions or to vary it rapidly in exact accordance with requirements. Three applications of control of this general type are described together with the methods used. The first application is to a null-type high-speed recorder, the second to a high-speed controller, and the third to a motor generator set held in synchronism with a source of frequency normally constant and at low power level.

High-Speed Recorder

One of the principal problems in designing a high-speed recorder is to move the pen or stylus to its final position within the allowed time without overshooting. If the quantity being measured, after making an abrupt change, holds constant at its new value until the chart paper has advanced sufficiently for the pen to draw a short section of straight line, then, any overshooting of the pen if present can be recognized as such and the record can be interpreted without serious error. However, the measured quantity may not be constant at its new value, in which case overshooting is very objectionable because it is impossible to distinguish between overshooting and the true maximum or minimum value of the measured quantity.

In the case of a null-type instrument, such as a slide-wire recorder, inertia is generally large, which fact tends to accentuate overshooting. Inertia is generally large because of certain accessories, and allowance for such accessories, as control disks, slide-wire transmitters, Selsyn transmitters, etc. By avoiding these accessories and redesigning with lighter parts the overshooting can be reduced,[5] but a very good way to eliminate overshooting entirely and at the same time have rugged parts and retain the accessories is to reduce the speed as the balance point is approached.

One way of reducing speed is to reduce motor input, but in general motor input is a poor index of motor speed because of the effect of inertia load, variable friction load, and the limitations of motor characteristics.[6,7] Ways of reducing the speed more definitely have been investigated and it has been found to be most satisfactory to use an electric tachometer to measure speed and control it.

With the use of the tachometer, the motor requirements are simplified. It need only be capable of meeting the maximum torque demand and should, of course, have minimum inertia if maximum speed of recording is desired. A series commutator motor serves very well. The field turns are reduced somewhat below standard d-c practice. This reduces field inductance and gives better performance on the pulsating output of the thyratrons.

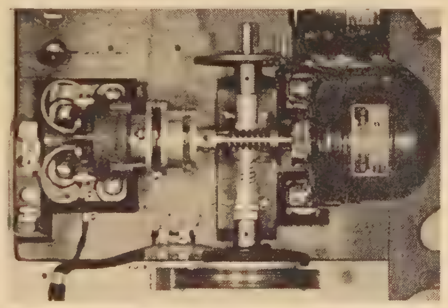

Figure 1. Motor and coupled tachometer

The d-c tachometer for controlling the motor speed is flexibly coupled to an extension of the motor shaft

Figure 2. Combined motor tachometer unit

The d-c tachometer for controlling the motor speed is built into a common frame with the motor

The tachometer is nothing more than a d-c generator with a permanent-magnet field. Figure 1 shows it as a separate unit coupled to the motor through a coupling designed to have maximum torsional stiffness. Figure 2 shows it built integral with the motor.

The motor receives its power through one or the other of a pair of thyratrons, for forward or reverse torque, as required. The connections are indicated schematically in figure 3. This figure shows the recorder as a d-c potentiometer of low range ($2^1/_2$ millivolts).[6] The current through the slide-wire potentiometer is set at a fixed value so that each and every position of the slide-wire contact corresponds to a known voltage and, since the pen moves with the contact as it is driven to the balance point by the motor, the pen position indicates the value of the measured electromotive force.

Any unbalance is detected by a vacuum-tube amplifier. This is not a d-c amplifier as might be supposed. In general d-c amplifiers are subject to a drift in zero. Instead an a-c amplifier is used which can have slight drifts in sensitivity but no drift in zero.

The a-c signal for the amplifier is derived from the unbalanced d-c voltage by the action of a carbon-microphone modulator driven at approximately constant amplitude at line frequency. This form of detector is fast and free from the effects of vibration.

In operation, if there is a sudden decrease in the electromotive force being measured, there will be an unbalanced d-c voltage in this circuit. A current will flow, the microphone will modulate the current, that is, it will produce an a-c component. The a-c component in passing through the primary winding of the low-level transformer will develop an a-c voltage across it. The secondary winding will apply a stepped-up a-c voltage to the amplifier. The amplifier output is connected to a push-pull transformer which in turn is connected to the grids of the thyratrons. The thyratron plates are supplied with an a-c voltage having a definite phase relation to the microphone drive. In one or the other of these thyratrons, the grid will be positive when the plate is positive and this tube will pass current, thus urging the motor to drive the pen downscale.

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[1] For all numbered references, see list at end of paper.

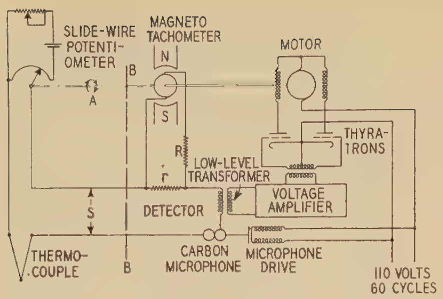

Figure 3. Simplified diagram of potentiometer recorder

As shown, the circuit is arranged for recording the voltage of a thermocouple. When used as a controller the part to the right of *B-B* is unchanged except for the addition of an inductance in series with *R*

If, instead of a sudden decrease, there is a sudden increase of the measured electromotive force the unbalanced direct current will be in the opposite direction, the phase of the alternating current applied to the amplifier will be reversed, so that the grid of the other thyratron will be positive when its plate is positive. It will pass current and urge the motor to drive the pen upscale.

If there is no unbalance there will be no direct current through the microphone, there will be no a-c component, and no motor current.

From this it can be seen that, if the recorder is balanced, it will stay balanced, and if it is unbalanced, it will be urged toward the balanced position (with full torque).

If the recorder consisted of nothing more than this, it would overshoot (and possibly oscillate) due to inertia of the parts, hence the use of the tachometer.

The tachometer voltage is attenuated by a pair of resistors connected as shown. This voltage is then introduced into the circuit of the measured electromotive force so that in operation, the speed of the motor is controlled to maintain the sum of all three voltages in this circuit at zero. In other words, the tachometer voltage is controlled to be equal to the difference between the measured electromotive force and the slide-wire electromotive force. Hence the speed of rebalance tends to be proportional to the remaining unbalance. In this way, the speed is reduced as the balance point is approached so that there can be no overshooting no matter how abrupt nor how large may be the change in the measured quantity.

It is of interest to consider a system of this general type in the case where the only limitations are a fixed torque and a fixed inertia. In this case, the quickest conceivable way to get the system balanced is to throw on full accelerating torque and leave it on up to a certain critical time, at which time the torque should be reversed. If the time be correctly chosen for reversal the system will just come to rest at the balance point. This time can be picked by using a tachometer with a voltage output proportional to the square of the speed. The method is effective for any magnitude of unbalance and for any position of the balance point. This is evident when one considers that the kinetic energy in the motor (and parts that move with it) increases in proportion to the square of the speed and that this energy must never be allowed to exceed that which can be absorbed subsequently by the braking of the motor. The energy which can be absorbed decreases directly with the remaining distance to the balance point.

At every instant the voltage from the square-law tachometer indicates the kinetic energy and the remaining unbalanced voltage indicates the energy which can be absorbed by braking, so, as soon as the former voltage equals the latter, the accelerating torque is turned off and the braking torque is turned on.

In practice, it has been found that the nonlinear current-voltage curve of a copper–copper oxide rectifier[8] when used with a linear tachometer gives a very satisfactory square-law tachometer as indicated by the resulting performance shown in figure 5. It may be noticed that the point of maximum speed does not occur exactly half way toward balance either in distance or in time as it would in the limiting case. The greater time given to deceleration is the result of a margin of safety in the adjustment of the tachometer voltage in order that overshooting may not occur under the worst combination of adverse conditions.

High-Speed Controller

Those familiar with problems of automatic control will recognize in the recorder system just described some features and elements well suited to automatic control. Refer to figure 3 and consider the system to the right of *B-B* as a controller. Disregard the part of figure 3 to the left of *B-B* and consider instead that there is here substituted the machine or system to be controlled. *S* is an electromotive force which indicates the deviation from normal of the controlled variable such as speed or temperature. *A* is the position of the control motor shaft and also the position of the rheostat or valve or whatever is involved, but which, in any case, if changed, will sooner or later affect the deviation voltage *S*.

From the description of the recorder already given (and with a linear tachometer) it is evident that the shaft will be moved at a speed proportional to the deviation voltage *S*. That is:

$$\frac{dA}{dt} = K_1S \qquad (1)$$

where t is time and K_1 is a constant. This well-known type of control,[9] which is quite satisfactory for the recorder, is likely to be quite unsatisfactory for controlling a machine or system which in itself has delay or time lag. Quite often if set up to operate with speed sufficient to be useful, it will hunt or cycle.

If the effect of the tachometer is reduced to a negligible amount by increasing R or decreasing r (figure 3) and if at the same time a slide-wire potentiometer with its output connected in series with the deviation voltage S is placed upon the control motor shaft, then the position of the shaft will be controlled to be proportional to the deviation S. That is:

$$A = K_2S \qquad (2)$$

This well-known type of control[9] is not likely to hunt. It does not, however, reduce to zero the deviation from normal

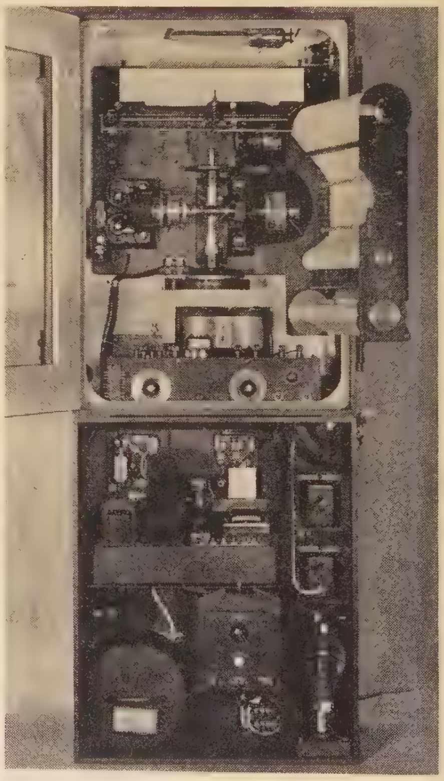

Figure 4. High-speed potentiometer recorder

The upper case contains the motor, tachometer, slide-wire, slide-wire rheostat, pen, and chart while the lower case contains the microphone, low-level transformer, voltage amplifier, and thyratrons unless equilibrium just happens to be reached for the normal position of the control motor shaft, A.

By omitting the slide-wire and placing in series with the tachometer, inductance as well as resistance we get the well-known type of control[9,10]

$$\frac{dA}{dt} = K_1S + K_3\frac{dS}{dt} \tag{3}$$

or

$$\frac{dA}{dt} = K_4\left(RS + L\frac{dS}{dt}\right)$$

where R is the resistance in ohms and L is the inductance in henries in the tachometer circuit. L is not shown in figure 3. K_4 is revolutions per second per volt in the tachometer divided by r (the coupling resistor) in ohms. S is the deviation in volts and A the position of the shaft in revolutions. t is time in seconds.

By choosing proper constants this control becomes as stable and fast as type (2) and reduces the deviation to zero as does type (1).

It is of interest that the complete control system uses no elements which are not used in the recorder with the exception of the inductance L. The motor tachometer unit figure 2 is mounted on the rheostat or valve of the system being controlled. This type of controller is of value for processes which require sensitivity and speed in their control, but which in themselves have too great a time lag to permit the use of a simple type of control. The magnitude of the process time lag that can be handled satisfactorily with this type of control is limited by the circuit elements available for use in the tachometer circuit in the controller. Principally, the limitation is in the time constant of these circuit elements.

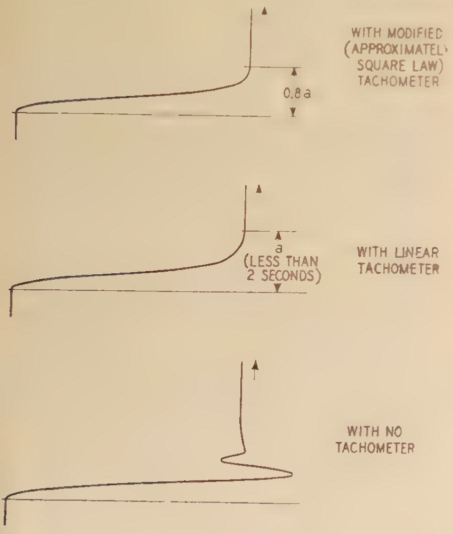

Figure 5. Recorder rebalancing curves

These curves show how overshooting can be eliminated and how the rebalancing time can be reduced by the proper use of a tachometer in a recorder

Synchronized Source of A-C Power

The problem here is to provide an a-c source of several hundred watts synchronized with a signal capable of supplying only a small fraction of a watt. The signal frequency is normally held constant at 60 cycles per second. One possibility is the use of a thyratron inverter, but in some applications a controlled motor-generator seems better suited, because tube capacity requirements are less, the output voltage can be made independent of input voltage variations, and tube failure causes only a loss of frequency control rather than a complete loss of voltage.

The generator is necessarily an a-c machine. The motor is a d-c machine, shunt (or compound) wound, and requires a d-c source of supply. The control of the speed of the shaft is the means whereby the frequency of the generator output is controlled. The speed is controlled by the action of a thyratron on the motor field. For the purpose of control the speed function is obtained by comparing the frequency of the generated a-c wave with the voltage wave of the standard signal. Hence in this application the a-c generator itself serves as the equivalent of a tachometer.

The thyratron is supplied with alternating voltage on its plate from the a-c generator (self-excited) and with alternating voltage on its grid from the controlling signal. In operation, if the machine slows down the plate voltage increases its lag with respect to the grid voltage, more current is passed which weakens the motor field until the speed is returned to normal.

If the cause of the slowing down remains, the field must continue in its somewhat weakened condition as a result of more thyratron current which in turn is maintained by a greater phase lag of the output voltage of the a-c generator with respect to the signal voltage. The control therefore sets motor field proportional to the relative angular *position* of the generator rotor.

When this system was still in the experimental stage and consisted of no more than that described above, it was found that full load variations could be taken care of readily, but that the d-c input voltage had to be maintained within rather close limits. This was not surprising because of the inherent characteristics of a shunt motor with field saturation of the usual amount. Changes in load require only small changes in field (even less if there is compounding), but changes in d-c input voltage require very considerable changes in field. A wide range of d-c input voltage, therefore, dictates that the maximum effect of the thyratron on the field be large. Since this large effect must reduce to zero as the advance in the rotor increases to only one-half of a cycle (180 electrical degrees), the phase control can be said to be "stiff."

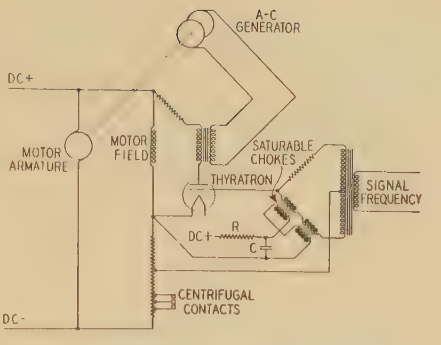

Figure 6. Simplified diagram of synchronized motor generator

This diagram shows, in addition to the basic control, how the voltage across the motor field is integrated by the RC circuit and how the result is used to modify the control

Stiffening the phase control increases the tendency to hunt; hence there is needed some means for counteracting this tendency so that the phase control can be made stiff enough to permit a satisfactory range of d-c input voltage.

The immediate effect of reducing the field on a shunt motor is to reduce the counter electromotive force, increase the armature current, and hence increase the torque. The simple control, as described so far, therefore makes the torque (angular *acceleration* of the rotor) proportional to the relative angular *position* of the rotor. Because it takes no account of the relative angular *velocity* of the rotor the oscillations are not definitely damped, hence the difficulty with hunting. It is not simple to take account of this relative *velocity* by measuring it directly, so instead it was decided to *integrate* the acceleration and to use the result to modify the control as will be explained. Since the *integral of acceleration* is *velocity*, this arrangement gives the desired damping effect and so allows a wide range of d-c input voltage.

A simplified circuit is given in figure 6. Normally the thyratron component of the field is determined by the phase relation between the alternator electromotive force and the signal electromotive force.

This is the basic control. To supply the damping effect this phase relation is modified by the saturable reactors in accordance with the strength of the motor field as indicated by the voltage across it, integrated by capacitance C which is charged and discharged through resistance R.

If the inductance of the saturable reactors decreases there is an advance of phase relative to the signal of the a-c voltage applied to the thyratron (grid to cathode). The saturable reactors are each standard permalloy core transformers and two are used with one winding reversed in order to eliminate transformer action.[11] Each core is saturated equally by a direct current determined by the d-c resistance of the reactors and the voltage across capacitor C. Theory and practice indicate that this current does not interfere with the functioning of C provided C is sufficiently large (50 microfarads).

In operation, when there is a shift in load or d-c input voltage, there is in general an angular shift of the rotor (relative to the signal). The rotor, as observed by a stroboscope, generally overshoots the final angle a few degrees, but after a few damped swings settles definitely into position. No cycles are lost so synchronism is maintained.

If at any time the d-c input voltage is momentarily interrupted or if the machine is overloaded, then synchronism will be lost. However, if conditions within the normal working range are restored before the motor starter drops out, the machine will resynchronize. This is accomplished by the assistance of the centrifugal contacts as shown in figure 6. These contacts play no part as long as the machine is running within a per cent or so of normal speed, one being closed and one being open at this speed. Their action in synchronizing is to cut in and out field resistance thus bringing the machine to within a per cent or so of synchronous speed from either the high or low side. From either of these speeds the machine can readily pull itself into synchronism.

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Lightning Protection of 22-Kv Substations

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ASSOCIATE AIEE

Synopsis: This paper outlines laboratory and field tests with a surge generator and cathode-ray oscillograph which led to the co-ordination of insulation and lightning-arrester performance in substations on the 22-kv subtransmission system of the Duquesne Light Company.

A basic level of 150 kv for station insulation was selected in 1932, and methods of obtaining this level are presented together with the operating record for five years. The index representing the station equipment faults in per cent of total system faults during thunderstorms has decreased 86 per cent following system-wide improvement programs modernizing insulation and arresters.

Recent papers on basic impulse insulation levels,[1] lightning arrester application,[2] and the general co-ordination problem[3,4] summarize a vast amount of work which has been done to place station lightning protection on a sound theoretical basis for the use of system designers and protection engineers.

Since 1932 the Duquesne Light Company has been actively engaged in an insulation co-ordination and lightning-arrester modernization program guided by this theory and based upon data obtained through laboratory and field tests with a 750-kv surge generator and cathode-ray oscillograph.

Because of the problems encountered in the protection of 22-kv station equipment, and the choice, in 1932, of 150 kv as a basic impulse insulation level, it is felt that a description of practice and results obtained would be timely.

The Problem

In the years 1930 and 1931 severe lightning seasons caused the number of substation equipment failures to reach such proportions that some measures to reduce them became imperative. It was already quite clear that any effective measures must be based upon accurate and voluminous data on the characteristics of equipment and protective devices.

The wide variety of insulation in use, together with little knowledge of the actual performance of various types of arrester, made it impossible to hope for an effective improvement program based upon data furnished by electrical equipment manufacturers. It was believed that only a comprehensive and fundamental attack would suffice, and in January 1932, a surge generator and cathode-ray oscillograph were installed in the high-voltage laboratory of the company.

Laboratory Tests

Kilovolt-time breakdown curves have been obtained for almost every insulation element of the system which is susceptible of such a measure. If a curve was not feasible, as in the case of transformers, minimum breakdown values have been ascertained which serve as approximate guides when considered with other data.

The characteristics of lightning arresters have been extensively studied in relation to the breakdown curves of the equipment to be protected.

Figure 1 illustrates typical laboratory tests to obtain these data. The arrester performance shown by the volt-time and volt-ampere oscillograms is representative of approximately 60 per cent of the arrester protection in service prior to 1932,

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[1] For all numbered references, see list at end of paper.

and reference to this performance will be made in the discussion which follows.

An important addition to these somewhat standardized tests was the devising and testing of methods to increase the strength of system elements which could not be replaced except at prohibitive cost.

Field Tests

The portability of the surge generator and cathode-ray oscillograph made it possible to test substations as a whole to determine points of maximum voltage caused by reflections, and to detect unsuspected weak insulation. Lightning arresters in service were tested—sometimes with startling results. In still other tests, bus and disconnect-switch insulators were flashed over, with no regard to the shape of the applied surge, and the results compared with those predicted by laboratory impulse breakdown curves. The upper curve of figure 2*a* shows a kilovolt time-lag curve of a two-unit pedestal insulator obtained in the laboratory. The lower curve is a replot of oscillogram 55-7, with zero time corresponding to the crest value of the 60-cycle breakdown, and is the record of the flashover of the same type of pedestal insulator installed on the bus of a transmission substation.

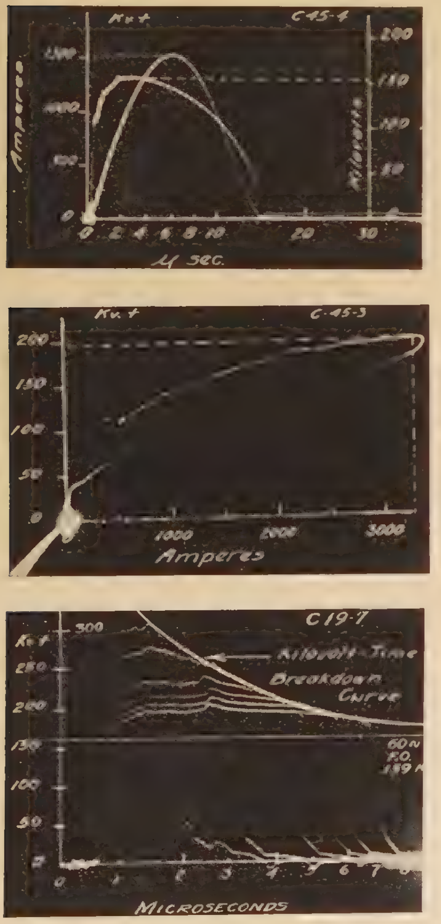

Figure 1. Typical laboratory tests

Oscillogram C45-3-4—25-kv arrester
Oscillogram C19-7—34.5-kv disconnect switch

Figure 2*b* shows a volt-time oscillogram of an arrester taken immediately after de-energizing it for field tests.

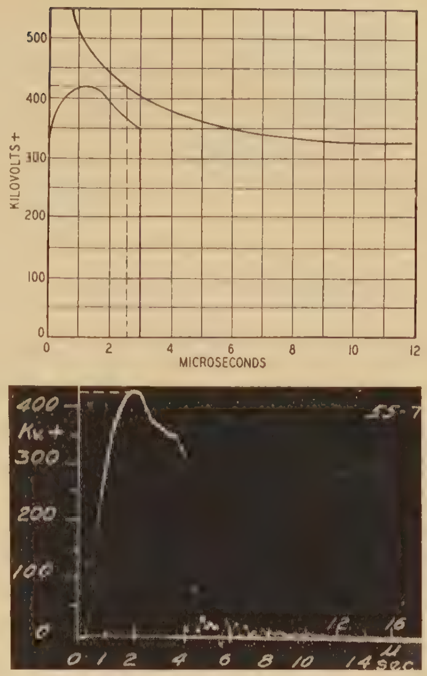

Figure 2a. Comparison of field test flashover with laboratory curve

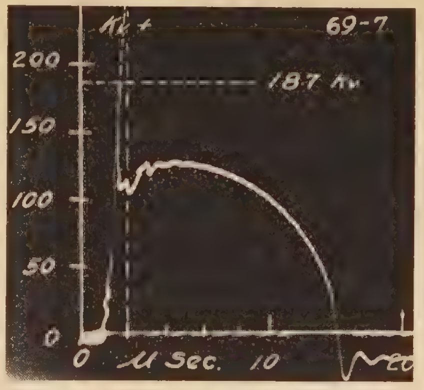

Figure 2b. Field test on 25-kv arrester, first impulse

Application of Data to System Improvement

When a cross section of the system insulation had been obtained, it became apparent that much of the indoor insulation was not protected by the arresters installed, at a moderate discharge current. Circuit breakers, disconnect switches, bus insulators, transformer bushings, and even some current transformer bushings and windings were found to have minimum impulse strength in the range from 100 kv to 150 kv.

A survey of all 22-kv indoor stations revealed that a basic level of 150 kv could be established by rebuilding certain types of circuit-breaker bushings, replacing bus and disconnect-switch insulators of low strength, and eliminating some obsolete equipment entirely.

Fortunately, the most widely used indoor disconnecting switch had a minimum breakdown of 150 kv, and this value was chosen as the minimum for all acceptable insulation. In some substations, special measures were required to bring the strength above the minimum set.

Figure 3 illustrates the relation between the arrester and typical kilovolt-time curves of insulation. Although curves are shown for a disconnect switch and three different circuit-breaker bushings, many other insulation elements would practically duplicate these curves.

Three types of circuit breaker were equipped with a bushing composed of an outer corrugated porcelain tube, an inner "Micarta" tube extending above and below the procelain, and a copper stud of much smaller diameter. The air space between the stud and tube was easily overstressed, and puncture of the Micarta tube followed by air flashover from the top of the porcelain to the circuit breaker operating mechanism was common. This defect was remedied by filling the air space with another close-fitting Micarta tube and increasing the length of the external portion of both tubes.

Other circuit-breaker bushings could neither be lengthened nor replaced, except at an unwarranted cost. In such cases the connection to the bushing was heavily taped, great care being exercised to exclude air pockets. Tests indicated that this expedient increased the impulse strength well above the basic level.

A great many transformer bushings possessed sufficient strength external to the transformer tank, but were very weak internally because of low air or oil surface clearances between the lead and the tank. Other bushings were adequate internally but were very weak externally. To solve this problem and reduce bushing stocks, a one-piece porcelain bushing was developed having adequate impulse strength externally and which extended below the oil level in all transformers. By means of flange adapters one bushing was made applicable to transformers of different manufacture.

In one station, subject to numerous bus failures, the entire bus of bare copper was removed and replaced with 22-kv varnished-cambric insulated wire. To avoid taped joints within the small com-

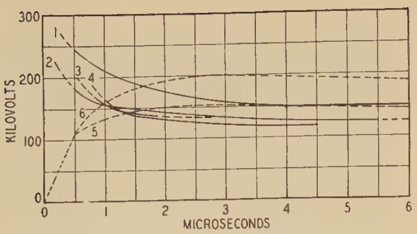

Figure 3. Typical performance of indoor equipment prior to co-ordination

Curve 1—Disconnect switch
Curves 2, 3, 4—Oil-circuit-breaker bushings
Curve 5—Arrester, 1,500 amperes in six microseconds
Curve 6—Arrester, 3,250 amperes in six microseconds

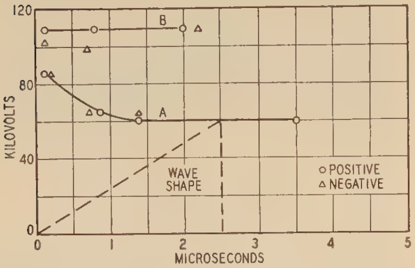

Figure 4. Breakdown of 25-kv line-type arresters

partment which would lower the impulse strength, the bus was run to each disconnect switch and then back to the compartment. The switch was at the basic level of 150 kv, and the bus much higher.

Figure 3 shows clearly that the basic level of 150 kv could not reliably be protected by the arrester whose performance is indicated. Further, insulation levels as high as 200 kv were endangered when the arrester discharge current exceeded 3,000 amperes. A general replacement program was necessary to establish system-wide arrester performance under the basic level.

Several designs of station and line-type arrester were critically tested, and from the results it was concluded that the protection provided by station type arresters was not sufficiently greater than that provided by line-type units to justify the greatly increased cost.

Two line-type units were decided upon and the replacement program begun. Figure 4 shows positive and negative break-down data on the two arresters *A* and *B*. Figure 5 shows a high current test on one of five impedance blocks used in the 25-kv arrester *A*.

Figure 6 illustrates the co-ordination of equipment insulation and the arrester performance for both light and heavy discharges. It is apparent that the maximum impedance drop of arrester *A* depends primarily on the rate of increase of discharge current, while that of arrester *B* depends upon the maximum magnitude of the discharge current. Laboratory tests and field experience indicate that the solid line curves are near the maximum voltages which the insulation of the arresters themselves will support, for the arrester is destroyed before curve 1 is reached.

In an attempt to obtain some idea of the winding strength of 22-kv transformers, a 667-kva single-phase 22-kv to 2.3-kv transformer was tested to breakdown with the results given in figure 7. Oscillogram 98-1 shows three full waves applied without a winding breakdown. Oscillogram 98-4 shows two winding breakdowns. The first winding breakdown occurred at an applied voltage of 210 kv on another test intermediate between those shown. The rarity of transformer failures makes it probable that the actual strength of most of the transformers is near 200 kv.

Since the outset of the co-ordination program, 408 circuit-breaker bushings, 388 transformer bushings, and 342 new arrester units have been installed. Numerous changes of other equipment and insulation have also been necessary to achieve impulse strength equal to or above the basic level.

System Performance After Improvements

Two methods were adopted to maintain as close a check as possible on the efficacy of the co-ordination program. The first of these was a systematic investigation of each individual station fault caused by lightning, and accurate recording of all line, cable, and station equipment faults during thunderstorms. The second method involved the selection of 13 stations notable for frequent lightning failures prior to the improvements, and the installation of lightning-arrester operation counters in these stations. This group is well scattered about the system and is thought to be a fairly representative sample. The operation recorder developed was energized by the current through the arrester, and it counted each distinct discharge.

Figure 8 gives index numbers for the total 22-kv line, cable, and station equipment faults; the station equipment faults alone; the station faults in per cent of the total faults; and the number of arrester operations recorded in the sample group of stations. To facilitate comparison of the first two data, the average of the 1930 and 1931 figures has been taken as 100. For the arrester operations, the average number of operations per year has been taken as 100. The correspondence between arrester operations and total faults merely reflects the fact that the number of surges which are virtually certain to exceed the basic station kilovolt level is proportional to the number of surges exceeding the line insulation at the point of origin. This conclusion is believed justified by the further facts that the average length of overhead line between stations is approximately two miles, and the line insulation ranges from a minimum of about 300 kv to over 1,000 kv. In this connection it is also well to remember that direct strokes to the line causing flashover to ground within a few spans of the station will result in voltages limited by the stroke current and the structure ground resistance, rather than by the structure insulation alone.

Although the impulse testing of equipment and arresters was begun in 1932, a number of arrester replacements and insulation improvements put into effect in 1931 were confirmed by the tests, and their influence on system performance is

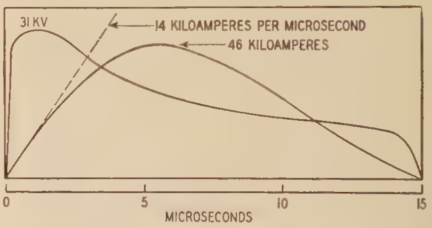

Figure 5. High-current test on one of five blocks used in arrester A

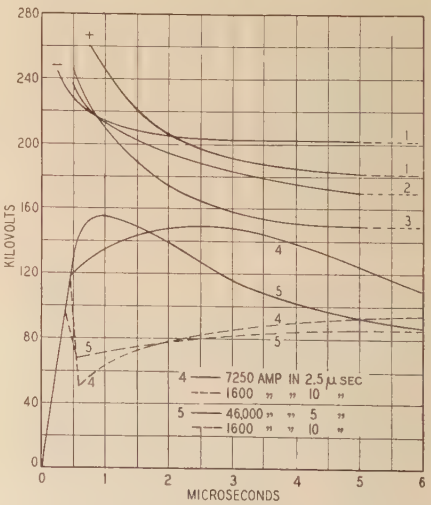

Figure 6. Typical co-ordination of indoor equipment after improvements

Curve 1—Transformer bushing
Curve 2—Oil-circuit-breaker bushing
Curve 3—Disconnect switch
Curve 4—Arrester *B*
Curve 5—Arrester *A*

shown in figure 8. Despite the fact that a slight increase in the actual number of station faults occurred in 1931, the weighed index giving these faults in per cent of total shows a decided drop.

In 1934 and 1935 the work was largely directed toward 66-kv transmission substation problems and 4-kv equipment protection, and this divergence is strikingly revealed by the index numbers. Again, further 22-kv improvements were put into effect late in 1935, and the 1936 record was still better.

Conclusions

The widely varying conditions encountered on subtransmission systems make it difficult to generalize the results of this program in any valid manner. The co-ordination of insulation and arresters has been in accordance with the present recommended basic level of 150 kv. Considerations of cost and space limitations dictated the choice of this level at the beginning of the co-ordination program in 1932, and the result of five years' operating experience are given in this paper. For systems having insulation and arrester performance whose relation to the basic level is comparable to that of figures 1 and 3, and whose exposure to surges is of the same degree as that cited, one may anticipate that similar improvement in performance will accompany co-ordination based upon detailed knowledge of insulation and arrester characteristics.

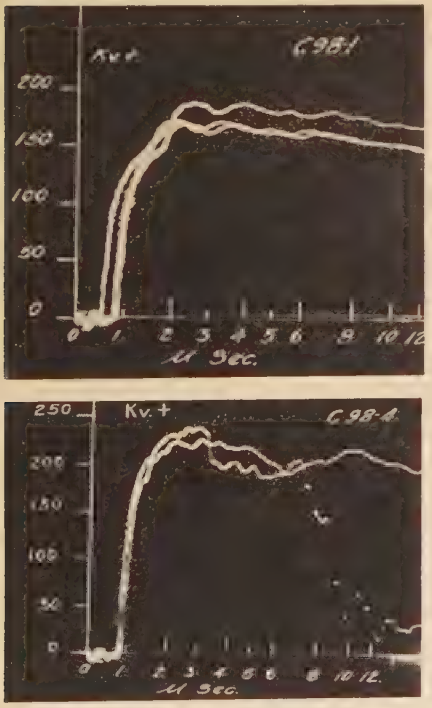

Figure 7. Winding breakdown tests on a 667-kva 22-kv to 2.3-kv transformer

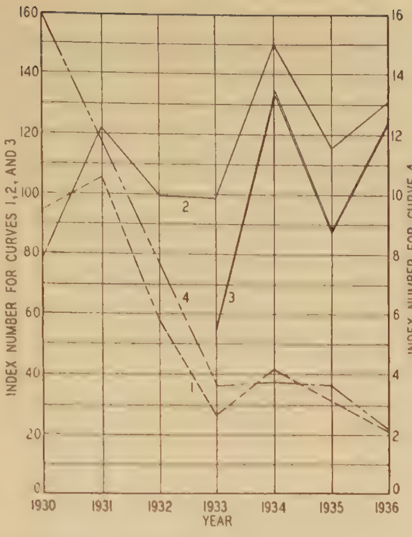

Figure 8. Lightning faults on 22-kv system

Curve 1—Station equipment faults
Curve 2—Total 22-kv faults
Curve 3—Station arrester operations
Curve 4—Station faults as per cent of total faults

Acknowledgments

The author wishes to express his appreciation of the liberal company policy which has made possible a fundamental attack on the lightning problem.

Particular acknowledgment is made of the work of Mr. D. B. Perrin who has been closely associated with the author throughout this work.

Mr. H. H. Marsh, Jr. has furthered the program by his interest in and appreciation of many problems of detail, and has been especially helpful in the preparation of the paper.

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Discussion

E. J. Allen (General Electric Company, Pittsfield, Mass.): This paper illustrates the practical benefits resulting from a comprehensive program of insulation co-ordination and protection. One of the most significant of these benefits is the great reduction in station faults caused by lightning in per cent of the total faults, after the co-ordination program was well under way in 1933. Figure 8 of the paper shows that although the total faults caused by lightning on the 22-kv system were higher in 1934 and 1936 than any other year since 1929, the percentage of station faults due to lightning has been steadily decreasing.

The choice of 150 kv as a basic impulse insulation level in 1932 for station equipment on this 22-kv system is the same as that more recently published by the EEI-NEMA Joint Committee.[1] As this paper concerns line-type lightning arresters, it is of timely interest to note the line-type lightning-arrester performance data[2] presented by the lightning arrester subcommittee. This report shows that the average impulse protective characteristics afforded by new designs of 25-kv line-type lightning arresters is less than 100 kv crest—representing over 50 per cent margin of protection to the 150-kv basic impulse insulation level.

Figure 1 of this discussion shows volt-time and ampere-time oscillograms taken on modern 25-kv Thyrite line-type lightning arresters at discharge currents of 1,790 and 5,600 crest amperes.

Figure 2 shows the general appearance of this type of arrester; employing unit type construction and containing Thyrite-shunted gaps and the main Thyrite valve element disks in the same housing. The impulse tests shown in figure 1 were obtained from a 25-kv arrester of the type shown second from the left-hand side of figure 2.

Calculations indicate that the maximum impulse wave of a 1,000-kv crest passed by the line insulation described by the author results in a lightning-arrester discharge current approximately 3,800 amperes at the line terminals, assuming 500-ohm line surge impedance. This seems to indicate that lightning-arrester discharge currents in service, except for possibly chopped waves resulting from direct lightning strokes contacting the line at a point close to the station, are well within the range of discharge currents up to 5,000 amperes, as set forth in the report of the lightning arrester subcommittee. Moreover, Messrs. McEachron and McMorris[3] have summarized the data in regard to lightning-discharge currents through lightning arresters located on primary distribution circuits rated 2,400 to 24,000 volts. These data show that 90 per cent of the discharge currents measured through lightning arresters are 5,000 amperes or less. These data apparently show that approximately 25 years may be expected to elapse for each discharge of at least 5,000 amperes through any one arrester.

Previous experience, together with the results shown in this paper, demonstrates the benefits resulting from a fundamental attack on the lightning problem. It is uneconomical and impractical to build into the connected apparatus sufficient insulation strength to withstand unmodified lightning voltage in service. Hence, lightning arresters affording ample margin of protection to apparatus insulation are the established economical basis of system co-ordination and protection.

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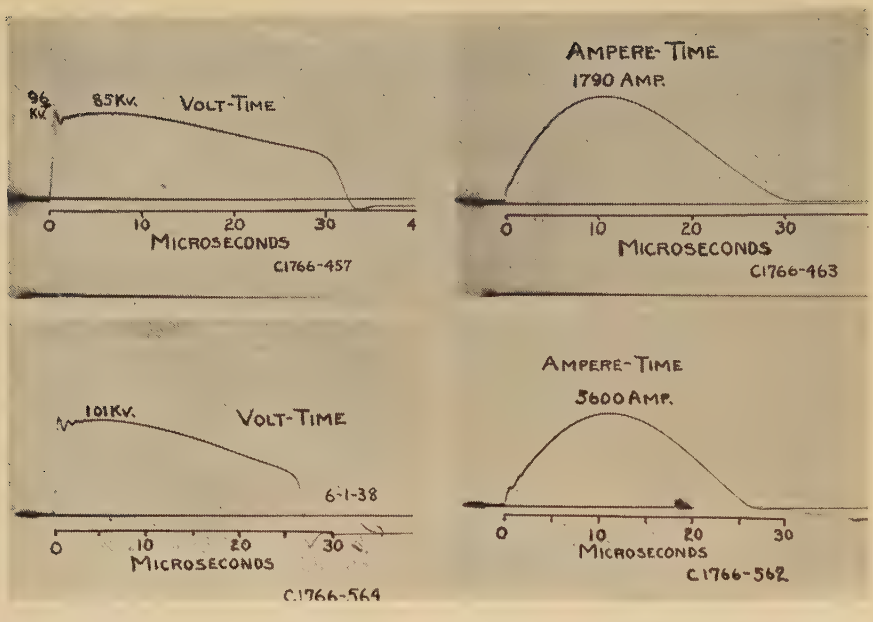

Figure 1. Impulse protective characteristics, Thyrite line-type lightning arrester, maximum rated 25 kv

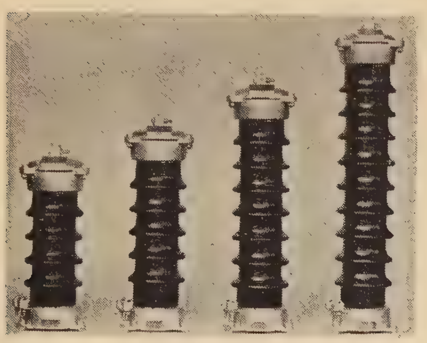

Figure 2. Thyrite line-type lightning arresters, maximum rated 20, 25, 30, and 37 kv, respectively

Co-ordination. ELECTRICAL ENGINEERING, volume 56, June 1937, page 711.

2. LINE TYPE LIGHTNING ARRESTER PERFORMANCE DATA, lightning arrester subcommittee. Summer convention, 1938, AIEE Technical Paper 38-56.

3. DISCHARGE CURRENTS IN DISTRIBUTION ARRESTERS—II, K. B. McEachron and W. A. McMorris. AIEE TRANSACTIONS, June 1938, volume 57, pages 307–12.

P. L. Bellaschi (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): Mr. Whitehead's paper presents a fine example of the application of insulation co-ordination, where it was thoroughly planned and well carried out to provide improved protection to 22-kv substations. At the time this work was initiated, impulse data on installed apparatus were rather meager. The wisdom, therefore, in using an impulse generator from the start is fully apparent from the results that have been achieved.

A point of particular interest is that Mr. Whitehead, starting out in 1932 in his co-ordination work, arrived after certain tests and analysis, to the conclusion that 150 kv for the 22-kv substations was a sound impulse insulation level to aim for. This is also the figure now prescribed by the EEI-NEMA Joint Committee on System Insulation Co-ordination. The coincidence is not, however, accidental since the processes in arriving at the levels are basically the same.

Figure 6 of the paper which shows the apparatus voltage-time curves (1, 2, and 3) of the substation apparatus above the established level and the characteristics of the protective devices below the level (curves 4 and 5) tell a very significant story of the technical and economic problems that had to be overcome to establish the 150-kv level. They also illustrate the principles in general on which the present insulation levels have been arrived and are based.

As stated in the paper, the insulation of the 22-kv lines ranges from 300 kv to over 1,000 kv. Presumably these low-voltage lines are not equipped with overhead ground wire. It is now quite well established from the field investigations here and abroad that the induced voltages seldom exceed 300 kv and from this consideration it then appears that the larger percentage of the impulse voltages entering the substation originate from direct strokes to the line.

Since there are two miles of line between two stations on the average, half of the strokes will travel one-half mile before entering a substation and therefore their severity would be attenuated somewhat. That the author has given consideration to direct strokes is clearly apparent from the arrester characteristics for high current discharges taken into consideration in figure 6. It would be of interest to have an expression of view from the author as to what extent direct strokes in the station or within one or two spans of the station represent the per cent of substation faults shown in figure 8 and what further measures are being considered to protect the substations against direct strokes.

J. T. Lusignan, Jr. (Ohio Brass Company, Mansfield): The author has described a fine example of a rather thorough insulation co-ordination program. The fact that it was possible to bring the surge generator and oscillograph to the substations in order to check the transient voltages there and the actual insulation provided to handle them is surely a fortunate circumstance. It is interesting to find, at least from the one example he shows (figure 2*a*), how well his measured insulator voltage values agree with the laboratory curve.

I find no mention of polarity in so far as flashover values are concerned. In insulation co-ordination the question often arises as to whether co-ordination should be on the basis of positive values only or both positive and negative values. I believe that field records show most severe direct strokes to be of negative polarity although many of the lower voltage lightning strokes are positive. If the stroke occurs to the conductor a surge of the same polarity obviously is imposed upon the insulation. A stroke to the ground wire or other nearby grounded object, of course, induces a surge of the opposite polarity upon the conductors. I am wondering what consideration Mr. Whitehead has given to this. For 22-kv insulators the positive and negative flashover values are often practically equal whether base or cap mounted. However, I am wondering whether there are other insulation breakdown points in a station which will exhibit sufficient polarity characteristics to warrant the latter being considered.

E. R. Whitehead: Mr. Allen presents performance data on the newly developed Thyrite distribution-type arrester. This line, of selected unit construction, appears to offer new possibilities for economy and flexibility in equipment protection.

The characteristics of the modern distribution-type arrester viewed in relation to the basic impulse levels and the McEachron-McMorris current distribution curves should provide a sound basis for their application.

Mr. Bellaschi raises a point of considerable interest. Prior to the co-ordination program it was not uncommon for weak station equipment to flash over during thunderstorms without an accompanying line fault. A combination of poor co-ordination and induced surges seems to explain this type of fault.

During the period covered by the paper, there has been a considerable increase in the use of wood crossarm braces and guy insulators. As a consequence most substation faults now correlate with direct-stroke line damage such as splintered braces, arms, or guys located within a very few spans of the station. The large number of stations involved in relation to the very small number of substation faults precludes any general use of direct-stroke protection on the 22-kv system. Consideration is now being given to auxiliary current-limiting schemes such as expulsion tubes or gaps one span from the station at the most exposed locations.

Doctor Lusignan asks what consideration has been given to polarity in the co-ordination studies. At the outset of the program it was essential to cover as many system elements as possible in a short time in order that early application of the data might be made. Positive-polarity time-lag curves were found to be lower than negative-polarity curves for most of the equipment, and therefore the earlier work was largely done with the former. In the later stages of the program both polarities were used.

Tests on Oil-Impregnated Paper—III

Fluid Flow

By **HUBERT H. RACE**
MEMBER AIEE

I. Introduction

IN TWO previous papers[1,2] we have described some of the results of life-test studies of miniature cable specimens started in 1934. One of the general observations resulting from a large number of tests is that all specimens made with high-density paper and standard-viscosity oil or specimens made with standard-density paper and high-viscosity oil have had short life at 30 kv whereas many specimens made with standard viscosity impregnant but otherwise identical have had very long life under the same conditions.

In attempting to explain these results we made the hypothesis that with either high-density paper or high-viscosity impregnant, the rate of flow of the impregnant through the paper during the cooling portion of the daily heat cycle was not great enough to prevent void formation. This would then result in ionization and early failure. We had all the data necessary to check this hypothesis except the flow characteristics of oil through paper. A search of the literature revealed little pertinent information although a considerable amount of work has been reported on the permeability of paper and other materials to air. A summary of this work and a bibliography of 31 references is given by Carson.[3] It is characteristic of all the work done on paper that the pressure head on the paper does not exceed a few centimeters of mercury and in Carson's work was limited to five to ten centimeters of water. This is due, of course, to trouble from deformation of unsupported sheets of paper at the higher pressures and also to certain convenient methods utilizing low heads. Goldberg performed some experiments of this type but neglected to take account of the expansion of the air as it passes through the paper. He noticed deviations at higher pressures and attributed these to turbulence, which is probably incorrect since we have used much higher rates of flow without turbulence. It also appears that his apparatus is subject to leakage, which can cause large errors.

A number of workers have investigated the flow of liquids through porous media.[5–16] Some of these have found anomalous results, which our preliminary work indicates was caused by the fact that the liquids used were not gas free. When the liquid contains gas, part of it comes out of solution as the pressure decreases, causing gas pockets in the paper, which decrease the rate of flow. This agrees with the work of Muskat[12] on mixtures of gas and oil flowing through sands although the latter work indicates other effects besides the formation of gas pockets. The only work we have found related to the flow of oil through paper is that of Whitehead and Greenfield,[17] relying on capillarity to produce the flow. However, we are not so much concerned with the flow in the plane of the paper as in the flow through it under hydraulic pressure.

Apparently few comparative studies have been made with different fluids on the same porous medium. Bull and Wronski[11] have made a comparative study with seven alcohols, carbon tetrachloride, and water in cellulose, glass, and carbon diaphragms with the interesting conclusion that the viscosity of the liquid was not the only property of the liquid important in determining the flow. No experiments at all have been reported, so far as we can determine, which give direct comparison between gas and liquid flow.

This paper gives the results of such a direct comparison together with studies of oil flow under varying conditions and the application of these data in determining limiting conditions causing void formation in cables.

II. Flow Equations

The flow of fluids through porous media can be expressed by Darcy's law (see reference 12),

$$\nu = (-K/\eta)\nabla p \qquad (1)$$

where ν is the vector rate of flow of the fluid, p the fluid pressure, η the viscosity of the fluid, and K a coefficient which has been called the "permeability" or flow constant of the porous medium. K may accordingly be defined as the volume of a homogeneous fluid of unit viscosity passing through a unit area in unit time under the influence of unit pressure gradient.

A. Flow of Oil Through Paper

In our experiments flat sheets of paper were used and the lines of flow through the test area A were everywhere normal to the paper. Consequently, the general flow equation 1 may be written in the one-dimensional form:

$$v_x = (-K/\eta)\,dp/dx \qquad (2)$$

In this case $v_x = Q/A$ where Q is the rate of flow of oil in cubic centimeters per second through the test area (A in square centimeters). Therefore,

$$Q = -(KA/\eta)(dp/dx) \qquad (3)$$

For steady state, with constant pressure difference and constant time rate of flow

$$dp/dx = -(p_1 - p_2)/NL \qquad (4)$$

where p_1 and p_2 are the inlet and outlet pressures in dynes per square centimeter, N is the number of layers of paper, and L is the thickness of one layer of paper in centimeters. Then

$$K = (Q/A)(\eta NL)/(p_1 - p_2) \qquad (5)$$

(η is in poises, that is, dynes times seconds divided by square centimeters, and K has the dimensions of an area).

B. Flow of Gases Through Paper

In dealing with the flow of gases through porous media, we may still use Darcy's law, and since the geometrical

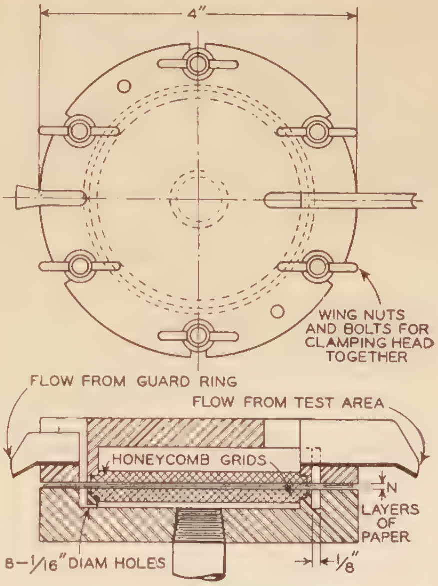

Figure 1. Oil-flow head

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Hubert H. Race is a research engineer for the General Electric Company, Schenectady, N. Y.

[1] For all numbered references, see list at end of paper.

features of our gas- and oil-flow apparatus are the same, equation 3 will also apply to gas flow. Due to the expansion of the gas as it passes to a region of lower pressure, it is convenient to express this relation in terms of the mass of gas flowing per second which we will call M. Then since

$$M = \rho Q \qquad (6)$$

where ρ is the density, we have from equation 3

$$M = -(KA\rho/\eta)(dp/dx) \qquad (7)$$

For gas flow dp/dx varies with x so that (7) will have to be integrated. In order to do this we assume Boyle's law to hold so that ρ/p is a constant, the temperature being assumed constant. The ratio may be taken at any condition (a), say at one atmosphere as a matter of convenience. Thus

$$\int_0^{NL} M dx = -\frac{KA}{\eta}\left(\frac{\rho_a}{p_a}\right)\int_{p_1}^{p_2} p dp$$

Integrating and rearranging we have

$$M = (KA/2\eta NL)(\rho_a/p_a)(p_1^2 - p_2^2) \qquad (8)$$

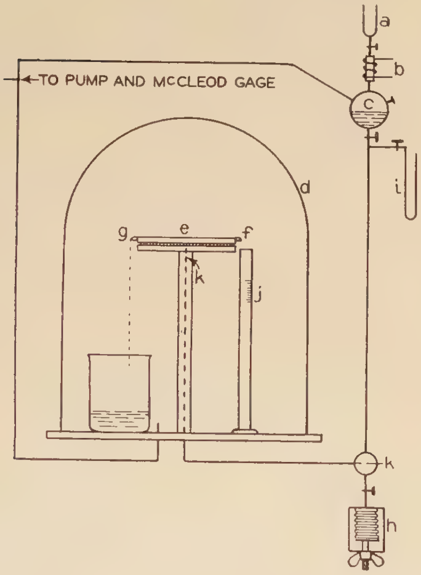

Figure 2. Essential features of oil-flow apparatus

- *a*—Filling reservoir
- *b*—Heater for degasifying oil
- *c*—Oil level during test
- *d*—Bell jar
- *e*—Head
- *f*—Overflow for test area
- *g*—Overflow for guard ring
- *h*—Sylphon bellows
- *i*—Mercury manometer
- *j*—Calibrated graduate cylinder for collecting oil from test area of paper
- *k*—Thermocouple leads

The determination of M can be made by direct measurement or by using a calibrated capillary. We have used the latter by allowing the gas to flow directly through the capillary after it leaves the measuring section of the paper. Consequently M is the same for the paper and the capillary. M may be determined for the capillary by the method described in Barr's "Monograph of Viscosity."[18] Although a radial component flow exists in the case of a gas flowing through a capillary, it has been found that Poiseuille's law of flow, which holds when the flow is strictly laminar, can be used if the rate of change of density with length is not too great.[18] This condition is realized in a long capillary of a fairly large diameter. Poiseuille's law is:

$$Q = -(\pi r^4/8\eta)(dp/dl) \qquad (9)$$

where r is the radius of the capillary, dl is an element of length, η the viscosity of the gas. As in equation 7 we replace Q by M/ρ

$$M = -(\pi r^4/8\eta)(\rho/p)\, p\,(dp/dl) \qquad (10)$$

and assume that the gas expands according to Boyle's law in passing through the capillary. Integrating (10)

$$\int_0^{l} M dl = -\frac{\pi r^4}{8\eta}\left(\frac{\rho_a}{p_a}\right)\int_{p_2}^{p_a} p dp$$

$$M = (\pi r^4/16\eta l)(\rho_a/p_a)(p_2^2 - p_a^2) \qquad (11)$$

Here η has been assumed to be independent of pressure as it is within wide limits (see reference 18 and also volume V of International Critical Tables, page 2). p_2 is the same as in (8) and p_a is the outlet pressure of the capillary (atmospheric in our apparatus). (ρ/p) is the same as in (8).

Equation 11 holds fairly well for rough measurements, but for accurate work it must be corrected for kinetic energy of the gas, end effects, slip and so on (see reference 18). The kinetic-energy correction is by far the largest correction; therefore, neglecting the others, equation 11 becomes

$$M = (\pi r^4/16\eta l)(\rho_a/p_a)(p_2^2 - p_a^2) - (1.1\, M^2/8\pi\eta l) \qquad (12)$$

K can now be calculated by eliminating M from equations 8 and 12.

Before this can be carried out numerically it is necessary to calibrate the capillary, that is, determine the factor $(\pi r^4/8l)$; l can be measured directly (33.8 centimeters in our case), but r, the radius, is not determined so easily. The usual practice is to partially fill the capillary with a thread of mercury, measure its length, weigh it, and from the density, weight, and length, determine its volume and from that the radius r. One may also test the uniformity of the bore by observing the length of the thread at various positions along the capillary.

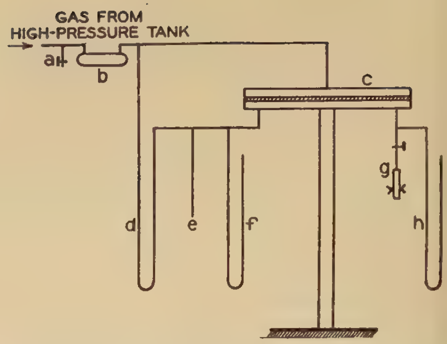

Figure 3. Essential features of gas-flow apparatus

- *a*—Stop cock for regulating pressure
- *b*—Phosphorus-pentoxide drying tube
- *c*—Head
- *d*—Differential manometer for measuring head across test area of paper
- *e*—Capillary
- *f*—Manometer for measuring head across capillary
- *g*—Stop and pinch cock arrangement for regulating head across guard area of paper
- *h*—Manometer for guard area of paper

Table I. Properties of Papers M and N

Property	M	N	Ratio M/N
Type	Kraft	Kraft	
Apparent density	0.75	1.10	0.68
Tensile strength (pounds per one-inch strip)			
Lengthwise	90	81	1.11
Crosswise	36	32	1.12
Per cent elongation			
Lengthwise	2.9	2.2	1.32
Crosswise	7.8	9.9	0.79
Tearing strength (grams, Elmendorf)			
Lengthwise	189	229	0.82
Crosswise	235	293	0.80
Per cent ash	0.56	0.52	
Alkalinity (milligrams of sulphuric acid per gram)	0.118	0.090	
Air resistance (seconds per mil, Gurley)	21	318	0.066 (Ratio N/M = 15.1)
Permeability K ($\times 10^{-12}$)			
Gas (N_2)	12.5	0.92	13.6
Liquid (oil A)	12.5	0.59	21.2

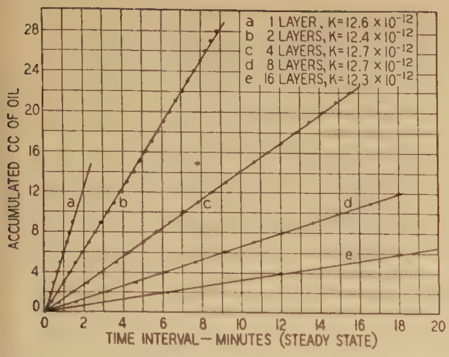

Figure 4. Oil-flow data on standard-density paper (M) for various numbers of layers

Our best determination of r^4 by this method was

$$r^4 = 70.8 \times 10^{-8} \text{ centimeters}^4$$

In using a capillary, care must be taken not to use such high rates of flow that turbulence occurs. The condition that the flow is not turbulent is that $R = \rho V d/\eta \leq 2{,}000$ (Reynolds' criterion. See International Critical Tables, volume V, page 2; also reference 19). Here ρ is the density, V linear velocity, η viscosity, d bore of capillary. For our capillary and our largest rate of flow R is about 35 so that we are working well below turbulent flow.

The question of turbulence may also be raised in connection with the paper. Here the bore diameters are all much smaller than that of the capillary and the linear velocity is also less than for the capillary. This means that R will be less than for the capillary and that turbulence cannot occur in the paper if it does not in the capillary.

In the calculations below, we use $(\pi r^4/16l) = 41.2 \times 10^{-10}$, $l = 33.8$ centimeters, and wherever $(p_a^2 - p_b^2)/p$ occurs multiply by $980.3 \times 13.53 = 1.328 \times 10^4$ (13.53 is the density of mercury to four places from 24.5 to 28.5 degrees centigrade) so that it is not necessary to convert pressures from centimeters of mercury to dynes per square centimeter. $A = 52.4$ centimeters. Then equation 12 becomes

$$M = 5.46 \times 10^{-5}(\rho_a/p_a)(p_2^2 - p_a^2) - 1.297 \times 10^{-3}M^2/\eta \quad (13)$$

and (8) is

$$K = 2.88 \times 10^{-6}\, NLM\eta\rho_a/p_a(p_1^2 - p_2^2) \quad (14)$$

III. Apparatus for Measuring Gas and Liquid Flow

The same geometrical arrangement has been used in both the gas-flow and oil-flow experiments. In both cases we wished to obtain data with pressure differences up to one atmosphere so that it was necessary to use supporting grids to prevent deformation of the paper under pressure. Although this introduces some uncertainty in the calculated area of flow, we assume that this does not affect the relative values of the gas and oil flow permeabilities. In all our calculations we have used the total area covered by the test section of the supporting grid.

In both the oil- and gas-flow experiments the paper was tightly clamped between the two halves of a device which we have called a head. Both heads are essentially the same, and the design of the oil-flow head is shown in figure 1. The test area is that area occupied by the honeycomb grids and it is the rate of flow through this area that comprises Q. In order to assure flow normal to the test area, a guard ring was provided in each case which had the same pressure drop across it as the test area. If the leakage through the edges is not too great this is an entirely satisfactory arrangement. Excessive leakage may be controlled by coating the edges of the paper with a plastic material which does not penetrate the test section. We used an air drying plastic Glyptal quite satisfactorily.

Figure 2 is a schematic diagram of the oil-flow apparatus. The apparatus is assembled as shown and thoroughly evacuated for several hours at a pressure of about one micron or less. The oil is introduced into the filling reservoir a, is allowed to trickle slowly through the heater b and into the bulb. This degasifies the oil. The oil was allowed to flow in at such a rate that the pressure of the system never exceeded about 25 microns. During the filling period the sylphon bellows was fully extended by means of the wing nut. The system was filled with oil up to a level c. The stopcock below c was then closed and the sylphon h released by loosening the wing nut. This puts approximately one atmosphere hydraulic pressure on the high-pressure side of the paper. The lower pressure is about 0.5 centimeter of oil plus the gas pressure, which was kept at about 0.1 micron throughout the tests. The oil from the test area flowed from f into the graduate j. The rate of flow was measured with an accurate stop watch and carefully calibrated graduate cylinder. In practice the manometer i was below the head so that the column of oil between the upper mercury level and the level of the paper had to be taken into account in calculating the pressure p_2.

The gas-flow head differs from figure 1 only in that pipe connections to the rest of the setup were used instead of overflow spouts. The arrangement of the gas-flow apparatus is shown schematically in figure 3; h is the manometer measuring the pressure above atmospheric of the guard area on the low-pressure side. Since the pressure on the top side of the paper is the same for both the guard area and the test area, the pressure drop across the guard area may be made equal to that across the test area by making the manometer reading Δh_1, of the guard manometer equal the reading Δh_2 of manometer f. This is done by bleeding off gas at g, which can be done only if there is not too much leakage at the edges of the paper.

If Δh_3 is the reading on manometer d, the pressures are as follows: $p_2 = p_a + \Delta h_2$, $p_1 = p_a + \Delta h_2 + \Delta h_3$. K can then be calculated from equations 12 and 8.

The gas for the gas-flow experiments was supplied by a tank of nitrogen at about 1,500 pounds per square inch pressure with a suitable reducing valve.

IV. Flow Data and Values of K

A. Oil Flow

The physical properties of the two grades of cable paper used are given in table I. The data and calculations for the oil-flow experiments are shown in table II. The slopes of the curves shown in figures 4, 5, and 6 are equal to Q for each of the indicated cases. Two or more runs on the same thickness of paper will not necessarily give the same rate of flow Q due to differences in viscosity and density of oil, which vary with temperature, and also to the variation of atmospheric pressure from run to run. This is illustrated in curves (a) and (b) of figure

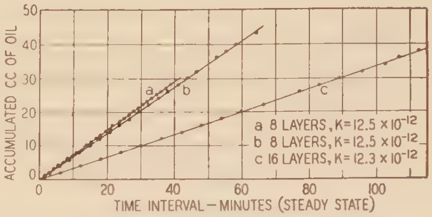

Figure 5. Oil-flow data on standard-density paper (M) for various numbers of layers

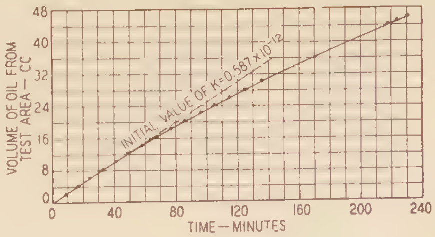

Figure 6. Oil-flow data, one sheet high-density cable paper (N)

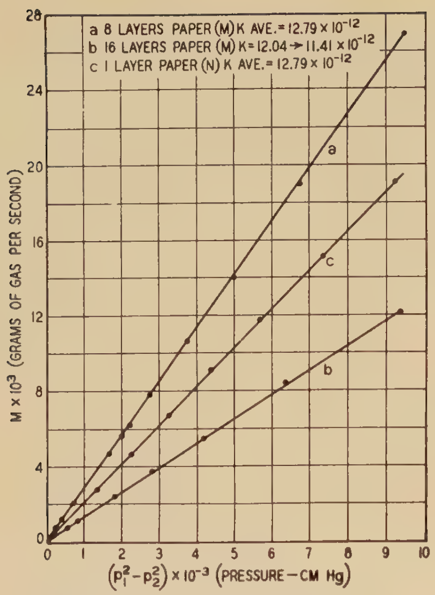

Figure 7. Flow of N_2 through cable paper

5, which give the same value for K although the slopes of the curves are somewhat different. For the same reason the slope of the curve for eight layers will probably not be exactly twice that for four layers [(*c*) and (*d*) of figure 4].

The value of K in table II for paper (N) was calculated for the first seven points of the curve (figure 6), which are sensibly a straight line ($K = 0.587 \times 10^{-12}$). From then on the rate of flow decreased, indicating the possibility of some slow swelling or rearrangement of the fibers in this highly calendered paper.

B. GAS FLOW

The data for these tests are in table III and figure 7 shows plots of the mass rate of flow M versus $(p_1^2 - p_2^2)$, which should be straight lines if K is a constant. The only one showing a deviation from constancy is that for 16 layers of paper (M). The permeability K decreases slowly (see table III), but the curve (*b*) shows only a slight deviation from linearity. Curve (*a*), figure 7, is for eight sheets of paper (M). Oil-flow test number 6 was made on these same eight sheets after taking the gas-flow data. Similarly, curve (*c*) is for the same sheet of paper (N) that was used later in the oil-flow test.

Discussion. The gas-flow data for eight sheets of paper (M) give a value of $K = 12.79 \times 10^{-12}$, which is slightly greater than the value from oil-flow data. It is not unreasonable to expect this inasmuch as some of the pores may be so small as to prevent oil flow. This may be expected from the appreciable rigidity of very thin layers of liquids. We are inclined to believe that the lower value of K obtained for 16 layers and the regular variations are not real but may be due to leakage through the edges. This is possible for a thick test specimen even when the guard ring has the same pressure drop as the test area. Moreover, examination of the formulas indicates that the calculated value of K will be reduced by such leaks.

In the high-density paper the resistance to gas flow was roughly 14 times greater than in the low-density paper whereas the resistance to oil flow was initially 21 times greater than in the low-density paper. (See table I.)

While the average density of the high-density paper (N) is only about 40 per cent greater than for the standard density paper (M), the process of manufacture of the former gives it surface layers of very closely packed fibers so that the major resistance to fluid flow is in these surface layers, thus explaining the relatively large effect on flow characteristics.

It should be noted that the above relations and results are for steady-state conditions only and are not expected to hold either when the paper is only partially saturated or when the liquid contains gases in solution or materials that will be adsorbed or filtered out by the paper, thus decreasing the effective capillary area.

V. Application of Flow Data to Conditions for Void Formation in Gas-Free Cables

A. ASSUMPTIONS

In studying the application of these data to the problem of void formation in cables we shall assume the following conditions:

1. The partial pressure of gas in the paper and impregnant is negligible, that is, the cable is virtually gas free.
2. The core dose not act as an oil reservoir so that during cooling all the impregnant required to keep the paper full must flow in from the outside.
3. The flow is radial, no longitudinal flow in the paper being considered.
4. Contraction of the paper fibers themselves is negligible.
5. A sufficient reservoir of impregnant is maintained on the outside circumference of the paper.

B. HYDRAULIC PRESSURE NECESSARY TO KEEP PAPER FULL

Let figure 8 represent the cross section of a cable in which we wish to determine the hydraulic pressure necessary to keep the interstices of the paper full of impregnant during cooling by uniform radial flow from the outside.

Let q = the total flow per centimeter length into the shaded cylinder to supply the interstices. Then

$$q = \pi\sigma s C(r^2 - r_1^2) \qquad (15)$$

where

σ = the coefficient of expansion of the impregnant in cubic centimeters per cubic centimeter per degree centigrade.
s = the space factor, that is, the ratio of the volume occupied by the impregnant to the total volume.
C = the rate of change of temperature in degrees centigrade per second.
r = radius in centimeters.

Then if V_r = the radial velocity of flow we have

$$V_r = -q/2\pi r = -\sigma s C[(r/2) - (r_1^2/2r)] \qquad (16)$$

Also, Darcy's law stated in radial coordinates gives

$$V_r = -(K/\eta)(dp/dr) \qquad (17)$$

Then eliminating V_r we have

$$(dp/dr) = (\sigma s C\eta/K)[(r/2) - (r_1^2/2r)] \qquad (18)$$

which when integrated gives

$$p = (\sigma s C\eta/K) \times [(r^2/4) - (r_1^2/2)\log_e r + \text{constant}] \qquad (19)$$

Assuming $p = 0$ at $r = r_1$, we obtain the following expression for the total pressure necessary to keep the interstices in the paper full between the radii r_1 and r_2.

$$p = (\sigma s C\eta/4K) \times [r_2^2 - r_1^2 - 2r_1^2 \log_e (r_2/r_1)] \qquad (20)$$

C. APPLICATION TO MINIATURE CABLE SPECIMENS

All but two of the factors in equation 20 are already known:

σ = 8×10^{-4} cubic centimeters per cubic centimeter per degree centigrade
s = 0.5
K = 12×10^{-12} for paper (M)
r_1 = $^3/_{16}$ inch = 0.476 centimeter
r_2 = r_1 + 0.065 inch = 0.641 centimeter

The remaining two factors must be considered together since we wish to consider the most severe condition which occurs when their product is a maximum. This

Table II. Oil-Flow Data

Paper	Average Thickness in Mils	Number of Layers	$K \times 10^{12}$
M	6.5	1	12.6
M		2	12.4
M		4	12.7
M		8	12.5
M		8	12.7
M		8	12.5
M		16	12.3
N	5	1	0.587

Table III. Gas-Flow Data

Paper	Average Thickness in Mils	Number of Layers	p_a	p_2	p_1	$M \times 10^3$	$K \times 10^{12}$
M	6.5	8	76.15	77.28	79.06	.805	12.79
M			76.15	77.87	80.49	1.242	13.37
M			76.15	79.14	83.63	2.132	13.02
M			76.11	82.73	92.17	4.75	12.80
M			76.42	85.15	97.31	6.32	12.69
M			75.03	83.05	94.33	5.64	12.68
M			75.03	86.09	100.87	7.83	12.72
M			75.03	89.99	108.93	10.62	12.67
M			75.03	94.58	117.95	13.96	12.63
M			75.47	101.54	130.95	18.98	12.66
M			75.47	112.12	148.47	27.00	12.67
M	6.5	16	76.24	77.41	81.12	.811	12.04
M			76.27	77.93	83.18	1.167	12.03
M			76.28	79.76	90.35	2.44	11.85
M			76.28	81.61	97.23	3.74	11.70
M			76.28	84.16	106.17	5.56	11.65
M			76.28	84.15	105.99	5.56	11.74
M			76.28	88.11	118.76	8.42	11.60
M			76.26	93.43	134.57	12.26	11.41
N	5	1	74.99	78.91	87.25	2.72	.887
N			74.98	81.54	94.48	4.67	.909
N			74.99	84.54	102.26	6.80	.926
N			74.97	87.83	109.84	9.12	.942
N			74.99	91.54	118.42	11.80	.940
N			74.99	96.09	128.64	15.18	.926
N			74.99	101.34	139.47	19.04	.925

maximum product can be obtained graphically as shown in figure 9. Curve (1) gives the daily cooling curve taken by means of a thermocouple inserted in a glass tube extending into the oil space surrounding one of the specimens. Since the rate of cooling is slow we shall assume that the temperature is the same throughout the specimen. Curve (2) gives the rate of cooling, that is, the first derivative of curve (1). Curve (3) shows the viscosity change in oil (0) as the specimen cools. Curve (4) is the product of curves (2) and (3). As the specimen cools it is seen that the viscosity increases faster than the rate of temperature change decreases so that the maximum value of $(C\eta)$ occurs as the specimen approaches room temperature. Thus in equation 20 we shall use $C\eta = 11 \times 10^{-3}$. Then $p = 4.59 \times 10^3$ dynes per square centimeter = 0.0045 atmosphere (one dyne per square centimeter = 0.987×10^{-6} atmosphere).

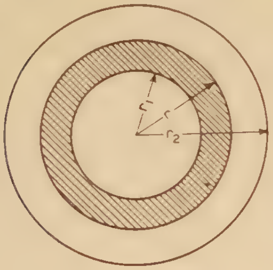

Figure 8. Cross section of a cable in which the space between radii r_1 and r_2 is occupied by paper + impregnant

In our miniature cable tests one atmosphere hydraulic pressure was maintained on the liquid surrounding the specimens so that void formation resulting from inability of the impregnant to flow in sufficient volume to keep the interstices in the paper full *was not* the primary cause of failure.

D. APPLICATION TO COMMERCIAL CABLE

To determine the order of magnitude of p for a commercial cable we shall assume the following data for a 69-kv solid-type cable recently installed in this country.

r_1 = 1.65 centimeters
r_2 = 3.40 centimeters
s = 0.5
σ = 8×10^{-4} cubic centimeters per cubic centimeter per degree centigrade
K = 24×10^{-12} (We have conducted a number of preliminary experiments to determine the average radial flow characteristics through and around standard density paper tapes of a machine insulated cable sample and found the rate of flow to be roughly double that through flat sheets.)
C = 11×10^{-3} (assuming the rate of temperature change in service to be the same as for our miniature specimen)

Then $p = 2.25 \times 10^5$ dynes per square centimeter = 0.222 atmosphere.

During cooling of a commercial cable, Halperin[20] shows that the hydraulic pressure in the impregnant at the sheath may drop as low as 0.16 atmosphere. Under such conditions *the hydraulic pressure would not be sufficient to keep the interstices in the paper full and void formation by this mechanism might be a significant factor in initiating ionization leading to ultimate failure.*

VI. Conclusions

1. Satisfactory equipment has been developed for absolute gas- and liquid-flow measurements through multiple layers of paper.

2. Using theoretical equations for gas and liquid flow in porous media the rate of flow of a gas-free liquid through standard-density cable paper can be calculated from air-flow data.

3. For super-calendered paper, the resistance to flow is much greater than would be indicated by the increase in average density, indicating the formation of a skin having high flow resistance on the surfaces of the paper sheet. Also the resistance to oil flow is greater than would be calculated from air-flow data and cannot be predicted from the latter, as is possible for standard-density paper. This indicates that some of the pores in the surface layers of super-calendered paper are so small that effects of absorption, adsorption, and the like on the surfaces of the cellulose fibers are no longer negligible.

4. These studies have shown that in our miniature cable samples, the resistance to flow was not great enough to cause void formation in the interstices of the paper insulation during cooling. The observed short life of specimens containing super-calendered paper or high-viscosity oil must have resulted from some other cause such as higher stress on the impregnant because of the higher dielectric constant of the paper.

5. In commercial solid-type cables using high-viscosity impregnants, on the other hand, calculations indicate that the hydraulic pressure available is not sufficient to keep the interstices of the paper full and

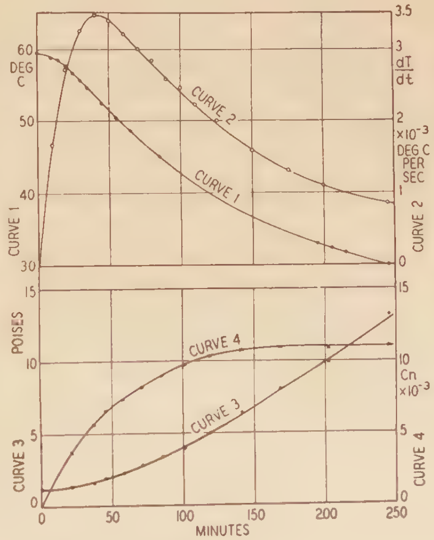

Figure 9. Determination of maximum value of $c\eta$

void formation is inevitable. This is the major argument for the use of low-viscosity impregnants and the "oil filled" principle in high-voltage cables.

Acknowledgment

The writer is happy to express appreciation to R. S. Kent, R. C. Retherford, and S. Godet for assistance in obtaining the information presented in this paper, and to H. Poritsky for checking the mathematical relations.

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Discussion

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): It is interesting to learn that gaseous ionization was not a factor responsible for the short life of some of Doctor Race's miniature cable samples. Unfortunately these investigations cannot be applied directly to the phenomena in actual cables as most of the assumptions under V-*A* of the paper will in general not apply in service. Further, in actual cables the flow through the tapes is only a portion of the total flow, a considerable part of which takes place through the spiral gaps between turns of tape. This means that the coefficient of friction of cable insulation for radial oil flow would be lower than for the author's samples. This is recognized in a parenthetical statement in part V-*D* of the paper.

Our tests on cables of the solid and oil-filled types indicate values of 4,000 to 18,000 pounds per square inch per inch thickness of insulation per cubic inch of oil per hour for oil having a viscosity of 1,000 centipoises. The value assumed by the author for 69-kv solid-type cable is 25,000 (same units), corresponding to the value of $K = 24 \times 10^{-12}$. For superdense cable insulation we find the radial coefficient of friction to be about ten times higher than for ordinary insulation, instead of 21 times as found by the author for his samples having superposed layers of paper. These lower coefficients of friction tend to reduce the probability of void formation.

In actual cables, the rate of temperature change during cooling will in general not be the same as in the laboratory models. Consideration must be given to the temperature gradient in the comparatively thick insulation of cables. The calculations on the possibility of void formation in commercial cables are over-simplified, particularly when applied to cables with thick insulation. The complete solution for pressure distribution in cable insulation was given by Miller and Wollaston in their paper "Thermal Transients and Oil Demands in Cables," AIEE Transactions, volume 52, March 1933, page 98. By the use of this method, we have found that negative pressures will not form in oil-filled cable, except possibly under extremely severe conditions. In solid-type cables having thick insulation and high-viscosity impregnant, negative pressures may easily occur due to insufficient hydrostatic pressure. It does not follow that this cause will of itself result in voids in the insulation.

Doctor Race considers the hydrostatic pressure to be the principal factor controlling the return of compound into the insulation after expansion. It seems that the surface tension and cohesion of the compound, the capillary forces of the paper, and the adhesion between compound and paper should also have been considered. These properties are important factors in void formation.

W. A. Del Mar (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): Doctor Race has done a nice piece of work in this paper in picking out of the complicated performance of a solid-type paper cable one or two separable items which are susceptible of theoretical treatment and partial verification by experiment. One must be careful, however, as indeed Doctor Race has been, not to draw conclusions of too general a character. Thus, it might appear from Doctor Race's paper that the essential defect of a solid-type cable is the radial transfer of oil from the interior to the exterior of the insulation, leaving voids in volume equivalent to the oil forced out of the insulation.

I do not believe that this is the whole story but that to a greater extent it is the entire insulation, paper and oil, that are expanded in volume during heating, leaving a larger volume of insulation to be filled by the same amount of oil.

Impregnated paper, unlike unimpregnated paper, will take a permanent set with practically any tensile stress. It will not retain all the stretch caused by a given tensile stress when that stress is withdrawn, but it will retain a considerable proportion, usually about 15 per cent, and that will account for the increased gross volume of insulation and, as this stretch is accompanied by a corresponding reduction in tape thickness, the void space will be further augmented.

Thus we see that while Doctor Race has picked one of the variables and given it an interesting theoretical treatment, there are other variables to be considered. Doctor Race, I know, appreciates this thoroughly but I have misgivings about his application of the formulas to a 69-kv cable, fearing that someone may take it too seriously as a practical tool in cable design.

R. J. Wiseman (The Okonite-Callender Cable Company, Inc., Passaic, N. J.): I am very much interested in Doctor Race's paper as it discusses the physical properties of impregnated paper insulation. We have had many technical papers dealing with the electrical characteristics, but unless we know how the oil moves through the paper, the effect of the fiber content of the paper on the oil movement, and the pressures necessary to cause the oil to flow, we do not get a complete picture of what takes place in a paper-insulated cable. Several years ago we started a similar research, but had to postpone active work due to the urgency of other researches. However, Doctor Race has gone into the subject much more accurately than we had planned.

This paper gives us a better appreciation of the relative effect of using low- and high-weight-density papers. We know in manufacture that it requires a longer time to dry and then impregnate high-density papers. This is confirmed by Doctor Race's work. In view of the much easier flow of oil through normal-density papers, the question arises as to the desirability of using a large percentage of high-density paper in a cable. Of course, this will have to be balanced against their relative electrical characteristics.

I wonder if the departure from a straight line for oil flow as given in figure 6 is partially due to the swelling of the fibers of the high-density paper which results in an increase in the thickness of the sheet under test as well as the closing up of the spaces between the fibers suggested by Doctor Race.

The attempts of Doctor Race to apply his test data to actual cables is to be commended as it puts his work on a practical basis. The difficulty of getting close agreement with actual cables is due to several factors, such as: the view expressed by Mr. Halperin regarding flow between the layers of the paper longitudinally and along the spiral gaps; the tightness of wrapping of the layers and the difference in temperature, that is, the temperature gradient between the conductor and the sheath. Doctor Race assumes the temperature is constant for any given instant of time. For very thin walls this is true, but for heavy walls it is not. The matter of the effect of tightness of wrapping could have been studied by having the flat sheets Doctor Race tested, subjected to various degrees of compression and then determine the oil flow. However, we have a better appreciation of how much pressure is needed to maintain saturation of a cable.

It is surprising that the pressure required is not very great and naturally, one may ask why do cables fail due to migration of oil and the formation of voids. In the so-called oil-filled type of cable we use a very thin oil and the pressures that we apply at joints are of such value that we can feed oil into all parts of the cable as rapidly as is necessary to maintain a positive pressure and we, therefore, do not get voids or insulation failures. It is the ideal cable. Of course, we have another solution in the high-pressure cables which use higher-viscosity oils, but always maintain saturation because the pressure will force the oil along the cable and into the insulation. However, we have many miles of solid-type cable and we will have many more miles in the years to come. We, therefore, should consider how we can improve the solid type of cable. At the present time we use a tight-fitting lead sheath on our cables which prevents easy flow of oil from the joint along the cable between the inside of the lead sheath and insulation. We do not have any follow-up of oil with moderate pressure to feed into the insulation as the cable cools. It is true that we experience stretched lead sheaths due to the expansion of the oil in localized points along the cable. We do not want this; rather we want to be able to permit easy flow of oil back and forth along the cable. Again, we use varnished cambric wrapped joints because of the shorter time to make a joint as compared to a paper wrapped joint and we seal off the strands of the conductor from the joint compound. We believe this also is wrong. We have studied both of these factors in our laboratories and have concluded that a porous type of joint which will permit oil to flow into and out of the strands of a conductor is the proper kind to use, particularly for high-voltage cables. This, with the loose lead sheath, will reduce the high pressures produced in a cable during the heating portion of the load cycle and prevent a high vacuum to occur during the cooling portion of the load cycle. We have shown by our tests that the life of a cable is increased thereby. Doctor Race has shown us that it does not take much pressure to maintain saturation in the insulation, provided we can supply the oil when needed.

H. H. Race: In general I agree with the ideas raised in the discussion of this paper. However, there are a few points on which I should like to emphasize a different interpretation.

It seems to me that the first sentence of Mr. Halperin's discussion is a misinterpretation of our data. In conclusion IV, I stated that "the resistance to flow was not great enough to cause void formation" in our miniature cable samples. However, this does not mean that *ionization* was not the cause of failure, in fact, in most cases I believe it was and have already submitted part IV of this series of papers entitled "Mechanism of Breakdown" giving the evidence.

The last sentence of paragraph 3 of Mr. Halperin's discussion also needs clarification. When a "solid type" cable cools no voids will form and the internal hydraulic pressure will remain positive so long as the lead envelope collapses or changes its shape so as to keep the total volume within the envelope equal to the volume of the solid and liquid materials within this envelope. However, lead has little true elasticity and therefore it undergoes permanent deformation easily, and follows such volume changes very imperfectly. When during cooling the sheath reaches a point beyond which it no longer follows the shrinkage of the materials within it, *voids inevitably form.* The gas pressure in these voids may be anywhere from less than one micron corresponding to the vapor pressure of the impregnant to a fairly high pressure, depending upon the temperature and how much residual moisture, air, or other gases are present. *The "solid type" cable in which no reservoirs are provided cannot be completely free from voids or gas pockets during cooling.* The electrical gradient at which ionization will start in such gas spaces depends upon a number of factors such as gas pressure, dimensions of the gas space, proximity to an electrode and the condition of the intervening solid dielectric.

A properly designed gas-free liquid-impregnated cable with sufficient reservoir capacity and liquid pressure is the only type in which voids or gas pockets cannot form during cooling.

Regarding Mr. Halperin's last paragraph, the factors he mentions certainly deserve consideration. As far as I know, however, their importance has not yet been measured quantitatively. As indicated by Mr. Delmar, the object of this paper was to give quantitative mathematical and experimental study to one factor, namely, viscous flow, which seemed most important.

The last paragraph of Mr. Wiseman's discussion advocates a partial attempt to make an "oil filled" cable out of a "solid type" cable by providing a loose sheath and porous joints so as to provide easy longitudinal flow of oil. To complete the system reservoirs must also be supplied containing sufficient low viscosity oil to keep the system full and stop joints to prevent building up excess pressures at low spots in the system. Even with these modifications a solid type cable cannot be maintained free from voids at all times. Therefore, why not use a properly designed "oil filled" system in the beginning?

Application of Large Phase-Shifting Transformer on an Interconnected System Loop

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A GROUP of 132-kv and 66-kv transmission systems form a loop about 300 miles in circumference and connect many important generating stations and a number of load points in the western part of Pennsylvania and the eastern portion of Ohio.

When these systems are operated interconnected at all tying-in points except one 66-kv tie north of Pittsburgh, the power exchange can be readily controlled. When this tie is closed, however, a complete ring is formed with multiple paths and an uncontrollable circulating power flows around the loop. Under such conditions, controlling the division of load over the paths and the interchange between companies requires phase-shifting equipment.

The phase-shifting transformer which is described in this paper was installed at the above mentioned point in order to make it possible to provide an emergency supply of power. Under ordinary operating conditions, this tie is open and there is no transfer of power in either direction. When, however, an unusual emergency situation develops on either system, which cannot be handled by the generating capacity associated with that system, the phase-shifting transformer can be put into operation by closing the tie and emergency power can be transferred from one system to the other.

This paper describes the phase-angle problem, the system studies made to determine the type and capacity of regulating equipment needed for the tie line, including the results of interconnected system tests, and operating performance after the installation of new equipment.

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W. J. LYMAN is electrical planning engineer with the Duquesne Light Company, Pittsburgh, Pa.; J. R. NORTH is general technical engineer with the Commonwealth and Southern Corporation, Jackson, Mich.

Acknowledgment is made to the Ohio Edison Company, Ohio Power Company, Ohio Public Service Company, Pennsylvania Power Company, and the West Penn Power Company for their co-operation during the field tests; and also, to Messrs. W. C. Bryson and V. E. Hill of the Duquesne Light Company for their valuable assistance.

Characteristics of Interconnected Systems

The interconnected systems and their geographical layout are shown by figure 1. Large generating stations are located in the Pittsburgh area at Brunots Island, Reed, Colfax, and Springdale; in the Youngstown area at Toronto, New Castle, Lowellville, and Warren; and in the Canton-Akron area at Windsor, Akron, and Cleveland. The 66-kv tie line between Valley and Ellwood is normally operated open at Valley, and the closing of this tie in an emergency is the subject of this study.

A 30,000-kva quadrature regulator or phase shifter having a range of 5.7 degrees plus or minus is located at Salt Spring substation, Youngstown, in the 132-kv Warren circuit. At Colfax there is a 36,000-kva voltage regulator in the 132-kv tie line to Springdale. The kilowatt interchange over this tie line is controlled automatically by regulating the Colfax generator output.

The reactance of the component parts of the loop system is of considerable importance in this phase-angle study. A convenient graphical method was developed for illustrating the magnitude of the reactance and the interrelation of the various sections. This is shown on figure 2 with the relative electrical distances between the stations drawn to scale in terms of the reactance of the lines, transformers, bus reactors, etc. The lengths of the solid lines represent ohmic values at 132 kv. Where several paths are in parallel, the equivalent net reactance has been calculated and is indicated by the length of the dashed lines. It will be noted that the total net reactance around the loop is 465 ohms at 132 kv.

Phase Angle and Load Transfer

The flow of power current through a reactance results in a phase-angle difference between the voltages at both ends, as shown on figure 3*A*. The *IX* drop is nearly in quadrature with the line voltage. Conversely, the insertion of a quadrature voltage in a reactive circuit will cause the flow of power current. Reactive current creates an *IX* drop in phase with the line voltage (figure 3 *B*) and so produces no angular difference. Thus, quadrature voltage controls kilowatt power flow and in-phase voltage controls reactive flow (modified slightly by line resistances).

Due to the manner in which the loads and generating capacities are distributed around the loop shown in figure 2, the voltage drops in the various circuits do not cancel out, and there is usually a relatively large phase-angle difference between the voltages at the open point. If the 66-kv tie at Valley substation is closed, as much as 12,000 kw will circulate around the entire ring, passing through all the interconnection points. This uncontrollable circulating power would naturally upset normal interchange even for those companies not directly interested. It would also increase the load on several important lines and transformers, possibly necessitating increased capacity at certain points.

Hence, if the Duquesne Light Company and the Pennsylvania Power Company desire to interchange power, some of it will pass through the direct 66-kv tie and some around the opposite direction through the other systems, with no means of controlling the division over the various circuits. A phase-shifting transformer connected in the 66-kv tie at Valley would introduce a controlled

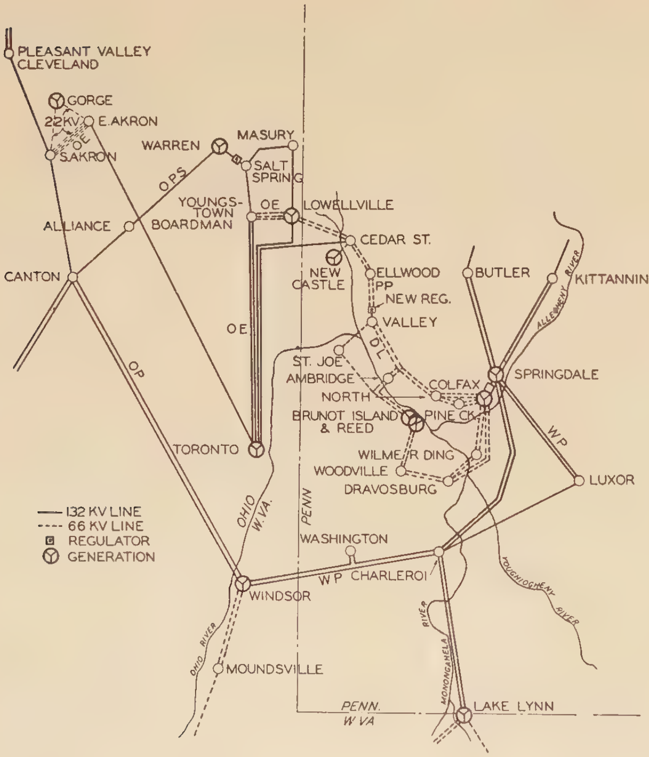

Figure 1. Pennsylvania–Ohio interconnected systems

DL—Duquesne Light Company
OE—Ohio Edison Company
OP—Ohio Power Company
OPS—Ohio Public Service Company
PP—Pennsylvania Power Company
WP—West Penn Power Company

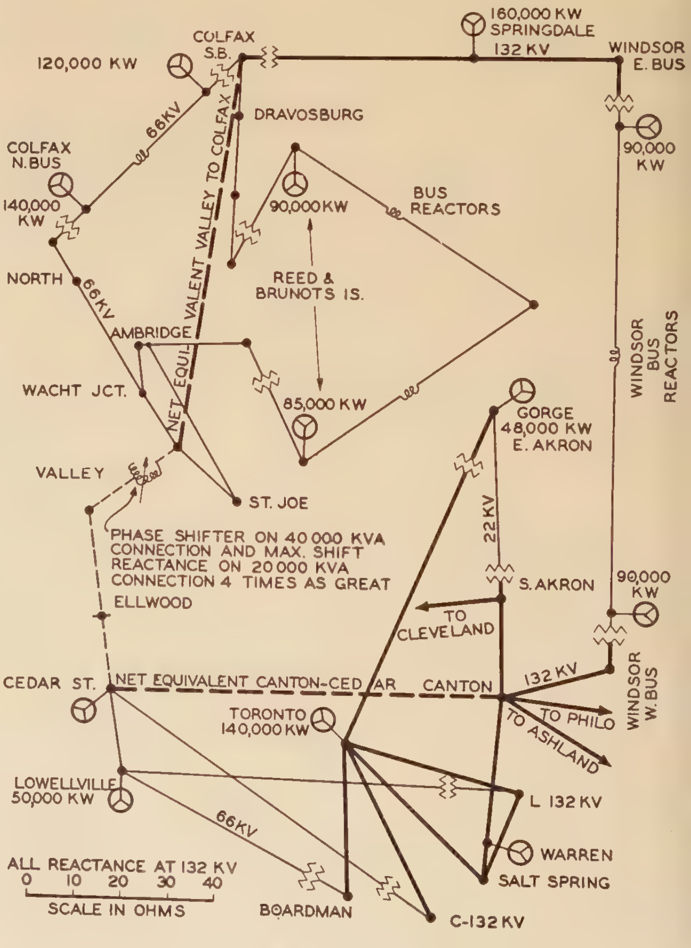

Figure 2. Equivalent reactance interconnected systems

Table I. Check of Phase Angles Around the Loop

October 1936 Tests

Circuit	Ohms per Circuit at 132 Kv	Phase Shift (Deg. per Megawatt)	Test No. 2—Normal				Test No. 4—Load Shift				Test 8a	
			10:40 A.M.		10:45 A.M.		3:50 P.M.		4:00 P.M.		3:15 P.M.	
			Megawatts	Degrees	Megawatts	Degrees	Megawatts	Degrees	Megawatts	Degrees	Megawatts	Degrees
Valley-Wacht Junction	33.9	0.111	12.0	1.33	8.5	0.94	8.5	0.94	8.5	0.94	9.0	1.00
Wacht Junction-North	48	0.157	25.4	3.99	22.2	3.49	15.8	2.48	18.1	2.85	23.1	3.63
North-Colfax	39.8	0.130	21.4	2.78	19.9	2.59	16.7	2.17	18.2	2.36	20.2	2.63
Colfax number 1 transformer	17	0.056	43.0	2.41	41.0	2.30	36.5	2.05	30.5	1.71	46.0	2.58
Colfax number 1 reactor	39.2	0.128	16.5	2.11	12.5	1.60	9.5	1.22	3.0	0.39	17.0	2.18
Colfax number 2 reactor	39.2	0.128	5.8	0.74	0.5	0.06	−4.5	−0.58	−9.5	−1.22	9.0	1.15
Colfax number 2 transformer	17	0.056	−31	−1.74	−30.5	−1.71	−22.0	−1.23	−22.0	−1.23	−30.0	−1.68
Springdale regulator and line	50.7	0.166	−3.8	−0.63	−13.4	−2.22	0	0	0	0	3.8	0.63
Springdale-Charleroi	76.5	0.087	−8.0	−0.70	−12.0	−1.04	−10	−0.87	−9.8	−0.85	−17.0	−1.48
Charleroi-Windsor	35.4	0.116	21.5	2.50	19	2.20	16	1.86	20.0	2.32	24.5	2.85
Number 4 transformer at Windsor	53.2	0.174	22.6	3.94	20	3.48	16	2.79	20.0	3.48	24.5	4.26
Number 4 reactor at Windsor	87	0.285			−5.5	−1.57						
Reactors number 2–4	0.174	0.571			−5.5	−3.15						
Number 1 transformer at Windsor	29.2	0.096	−11.0	−1.06	−15.5	−1.49	−5.5	−0.53	−3.5	−0.34	−1.0	−0.10
Windsor-Canton number 2	46	0.151	−11	−1.66	−15.5	−2.34	−5.5	−0.83	−3.5	−0.53	−1.0	−0.15
Canton-Akron	21.5	0.071	−33.5	−2.38	−36.0	−2.55	−36.5	−2.60	−21.3	−1.51	−22.5	−0.160
South Akron transformer	26	0.085	−27.5	−2.33	−31	−2.63	−29.0	−2.46	−13.8	−1.17	−28.7	−2.44
East number 2 line	0.154	0.505	− 6.0	−3.03	−4.6	−2.32	−4.0	−2.02	−7.0	−3.54	−4.5	−2.27
Akron number 1 line and transformer	79	0.259	42.0	10.90	40.0	10.37	38.0	9.87	46.5	12.07	53.7	13.94
Z-71 line and transformer	124	0.406	−6.7	−2.71	−8.9	−3.61	−5.9	−2.40	−6.5	−2.64	−6.2	−2.51
Y-53 line	34.2	0.112	−1.9	−0.21	−5.7	−0.64	−2.1	−0.24	−1.6	−0.18	−2.1	−0.24
Ellwood-Valley number 2	36.5	0.120	0		−9.6	−1.15	0		0		0	
Valley regulator	26.0	0.085	0		−9.6	−0.82	0		0		0	
Total angle—calculated				14.2		−0.21		9.62		12.9		22.4
Total angle—measured at Valley				14.0		0		7.0		13.5		28.0

quadrature voltage to compensate for the inherent angular difference and would permit satisfactory closed-ring operation when desired.

Field Tests—1928

The character of the problem of operating the 66-kv Valley interconnection closed simultaneously with the Colfax-Springdale interconnection was recognized many years ago, and the earliest effort to analyze the problem was a specially conducted series of tests in 1928. These tests consisted primarily of taking simultaneous readings on transformers and lines around the entire 300-mile loop, as it was at that time, and reading the actual phase difference between the voltages appearing across the open switch at Valley substation. These tests were described in an AIEE paper.[1]

Field Tests—1936

In 1936, it was decided to increase the interconnection capacity, largely as a result of the March 1936 flood. One of the increases proposed was a large capacity, 66-kv phase shifter in the Valley-Ellwood City tie, in order to permit parallel operation. In order to obtain accurate and up-to-date information from which to determine the required range of voltage and phase angle for the proposed regulator, another series of tests was run in the fall of 1936, similar to those performed in 1928.

These tests were conducted during the heavy load period, and arrangements were made to measure the voltages, the kilowatt and the kilovolt-ampere loads on the circuits around the loop, with the 66-kv tie at Valley open and closed, and with different divisions of load between the power generating stations. The test procedure was to take readings regularly every five minutes and to open and close the tie switch at a scheduled time between readings. In this way, data were secured with the Valley tie open and then again, five minutes later, with the tie closed, and vice versa.

Graphic records and indicating meter readings were obtained at the various points. At Valley substation, graphic records were secured of the kilowatt interchange, reactive kilovolt-ampere interchange, and the phase angle. The phase-angle record was secured on a wattmeter which had its potential coil energized from the Pennsylvania Power Company voltage through a metering transformer which shifted the voltage 90 degrees. The current coil was supplied by a constant current from the Duquesne Light Company system through a resistance load box. For diagram of connections, see reference 1. With this connection, the zero center wattmeter would read zero when the Duquesne Light Company and the Pennsylvania Power Company voltages were in phase. The readings were calibrated by use of a recording voltmeter and ammeter.

During the week following the tests, graphic charts were obtained of the voltages and phase angles. Figure 4*A* shows the phase angle variations and figure 4*B* illustrates the characteristic periodic oscillation of about five degrees occurring about 18 times per minute. This is probably the result of synchronizing power swings following the natural period of the combined system.

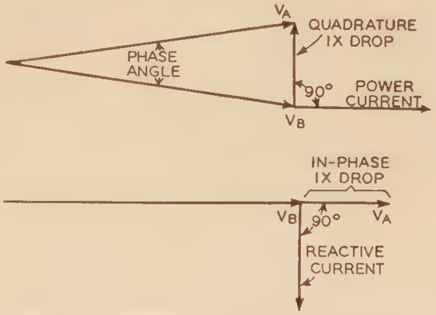

Figure 3. Relation between phase shift and power flow

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[1] For all numbered references, see list at end of paper.

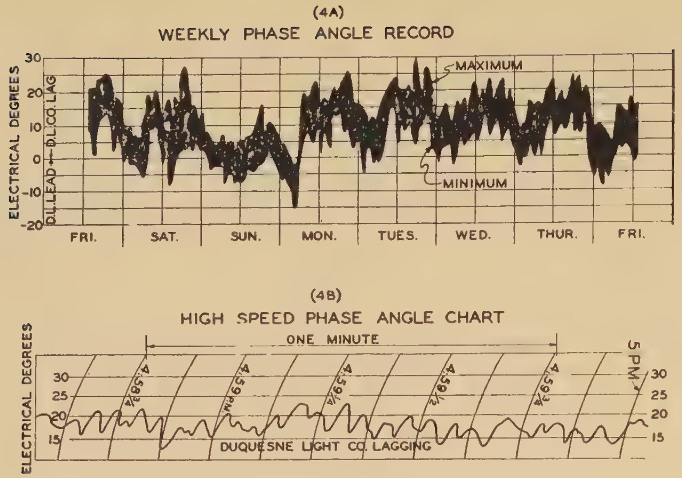


Figure 4. Phase-angle record

Summary of Test Results

One of the principal objectives of the test was to establish definitely the practicability of calculating phase angles for any given set of load conditions. The load readings were, therefore, used to calculate the phase angle and compare with the actual measured angle, and the results are shown on table I. The correspondence is very close, considering that the readings are taken from meters which are continuously fluctuating over a wide range.

Some typical power-flow and phase-angle test readings, as assembled and coordinated with the results, are shown on figures 5 and 6. It is interesting to study figure 5 and note that when the Valley tie is closed, the amount of circulating power passing through it actually appears at every point throughout the 300-mile loop. It may be seen passing through the Springdale interconnection, increasing the load on the Springdale-Charleroi lines, decreasing the load on the Charleroi-Windsor lines, and so on around the entire loop, with no effect on any of the generator loads. The automatic load control on the Colfax-Springdale tie was cut out during this test.

Figure 6 shows the charts for the interconnection at Valley substation. The relation between the phase angle with the tie switch open and the power flow immediately after closing the switch can readily be seen. During these tests the reactive kilovolt-amperes flowed in a direction opposite the power. This was due to the fact that the ratio of the original tie line autotransformer was not changed to transfer reactive power. Referring to figure 3*A*, the resistance in the system causes the current to lag behind the quadrature voltage by an angle less than 90 degrees. The circulating current, therefore, leads the line voltage.

On the 11:14 a.m. test (figure 6), 11,500 kw flowed through the Valley-Ellwood tie, and an equal amount was transferred from Colfax to Springdale. The automatic tie-line load control at Colfax was then cut in and set for zero interchange. By the time Colfax had backed off enough load to bring the Springdale tie down to zero, the Valley tie load had built up, as shown, to 22,000 kw. Efforts to control the phase angle by shifting as much as 20,000 kw between various plants did not result in changes of more than five degrees.

The normal open-circuit phase-angle difference between Valley and the Ellwood City lines during the load period 8 a.m. to 8 p.m. on week days varied between zero and plus 22 degrees (Ellwood "fast").

There is a rather definite relation between the phase angle across the open switch and the power which flows immediately on closing the switch. This ratio, as determined by test, runs from about 800 kw per degree at small angles down to 500 kw per degree for very large angles. This value may be checked analytically by taking the entire reactance around the loop, together with the voltage difference corresponding to a one degree phase angle. The result is as follows:

Reactance around loop = 465 ohms (at 132 kv)

Approximate impedance around loop = 472 ohms

Voltage corresponding to one degree =

$$V \sin 1° = \frac{0.0175 \times 132{,}000}{\sqrt{3}} = 1{,}333$$

$$I = \frac{1333}{472} = 2.82 \text{ amperes}$$

$$Kw = \sqrt{3}\,EI(PF) = \sqrt{3}\,(132{,}000)\ (2.82) \times \frac{465}{472} = 635 \text{ kw per degree}$$

These tests demonstrated that a phase shifter is necessary in order to use the Valley-Ellwood and the Colfax-Springdale ties simultaneously without splitting the Duquesne Light Company system into separate parts. The Valley location gives the most economical installation.

Load and Phase Angle Requirements

The range of phase-angle control required to attain the desired results is made up of two component parts: (*a*) the natural phase angle which may exist at any time due to the load and generating conditions and the resulting net power flow in each individual section of the entire loop, and (*b*) the quadrature voltage necessary to send the desired amount of power through the tie line in the proper direction. With a phase shifter capable of meeting these requirements, it would be possible to interchange power in the desired amount between the two adjacent systems without affecting in any way the generation, transmission line, or tie-line loads on the other systems involved in the loop.

The amount of phase shift needed to neutralize the natural angle involved a study of the characteristic load variations on the transmission lines and the effect of new generating capacity to be added in the future.

The limits set up for power interchange during an emergency were 40,000 kva from the Pennsylvania Power Company to the Duquesne Light Company, or 20,000 kva from the Duquesne Light Company to the Pennsylvania Power Company. These amounts are consistent with the requirements of each system and its ability to furnish power at that location.

Natural Phase Angle Between Systems

Obviously, it is not sufficient to know only what the normal phase angle will be in order to determine the phase shifter required. This phase difference varies over a wide range, depending on variations in the loads on the lines and transformers occasioned by changes in load, generation schedules, and emergency conditions. In general, the line loadings around the 300-mile ring tend to cancel out, and if the location of the loads and generation were entirely symmetrical, there would be no phase difference at Valley.

It is known, however, that load on lines feeding in one direction might possibly increase at the same time those feeding in the opposite direction would decrease. This would greatly increase (or decrease) the phase difference at Valley. It is entirely possible to secure extremely large angles in this manner, but if this occurrence is to be infrequent, it would not be economical to provide for it. Consequently, the proper solution cannot be reached by providing for the worst possible condition.

In order to reduce this problem to more definite and tangible terms, the probability theory was applied to the basic information to determine the likelihood that the angle will exceed any given amount in either direction. This analysis has been limited to the period from 8 a.m. to 8 p.m. on week days. The phase difference during light loads is much less.

The first step was to study the actual angular difference which existed and which could be measured at Valley substation. The combined result of many readings taken over several months is shown on figure 7. The angle varied from 0 to 22 degrees, with 11 degrees to 13 degrees occurring most frequently.

PROBABLE VARIATION

Most variable conditions which center about an average figure, but deviate from this average with a frequency which decreases as the deviation increases, can usually be represented by the standard "bell" shaped distribution or probability curve. The experience curve on figure 7 was plotted so as to show the percentage of the total number of readings of any particular angle. This curve has the characteristic "bell" shape and can be represented very closely, as shown by the series of crosses, with a standard curve.

The hourly loads of each individual line or transformer, when plotted as a frequency distribution curve, will follow this general "bell" shape, having a certain average value, and varying above and below this average or mean by an amount depending on how widely the load fluctuates (8 a.m. to 8 p.m. load period only being considered here). If the curve for each line and transformer were available, they could be converted into phase angles (by using the load and impedance) and combined to obtain a probability curve for the phase angle at Valley. The measure of the magnitude of the variation of a probability curve is called the standard deviation which is the root-mean-square of the deviations of all the individual points from the mean. It can be shown from the characteristics of the standard probability curve that the chances are two to one (2/3) that the load will not deviate from the mean by more than the standard deviation. Furthermore, the chance that the load will exceed any given amount may be determined from the probability curve or standard tables.

A study was made, therefore, of actual line load variations and representative probability curves obtained. The average value of the standard deviation for these curves was found to be 15 per cent of the average load during the 8 a.m. to 8 p.m. load period. This means that for only one-third of the time is the load more than 115 per cent or less than 85 per cent of the average.

If there are several lines and transformers in a loop, each carrying a load independent of the others, and varying approximately according to the standard probability curve, the net phase shift of the whole group will also be a probability or "bell" shaped curve. The "S.D." (standard deviation or spread) of this total curve will be the root-mean-square of the "S.D.'s" of the individual circuits.

Load changes due to a general increase in system loads will not greatly affect the angle since they will tend to balance out, and it is only the independent variations due to local conditions which affect the problem. It was found by examination of simultaneous loads around the loop that 30 per cent of the variation is common to all circuits, so that the effective standard deviation is only (100 per cent–30 per cent) × 15 per cent, or about

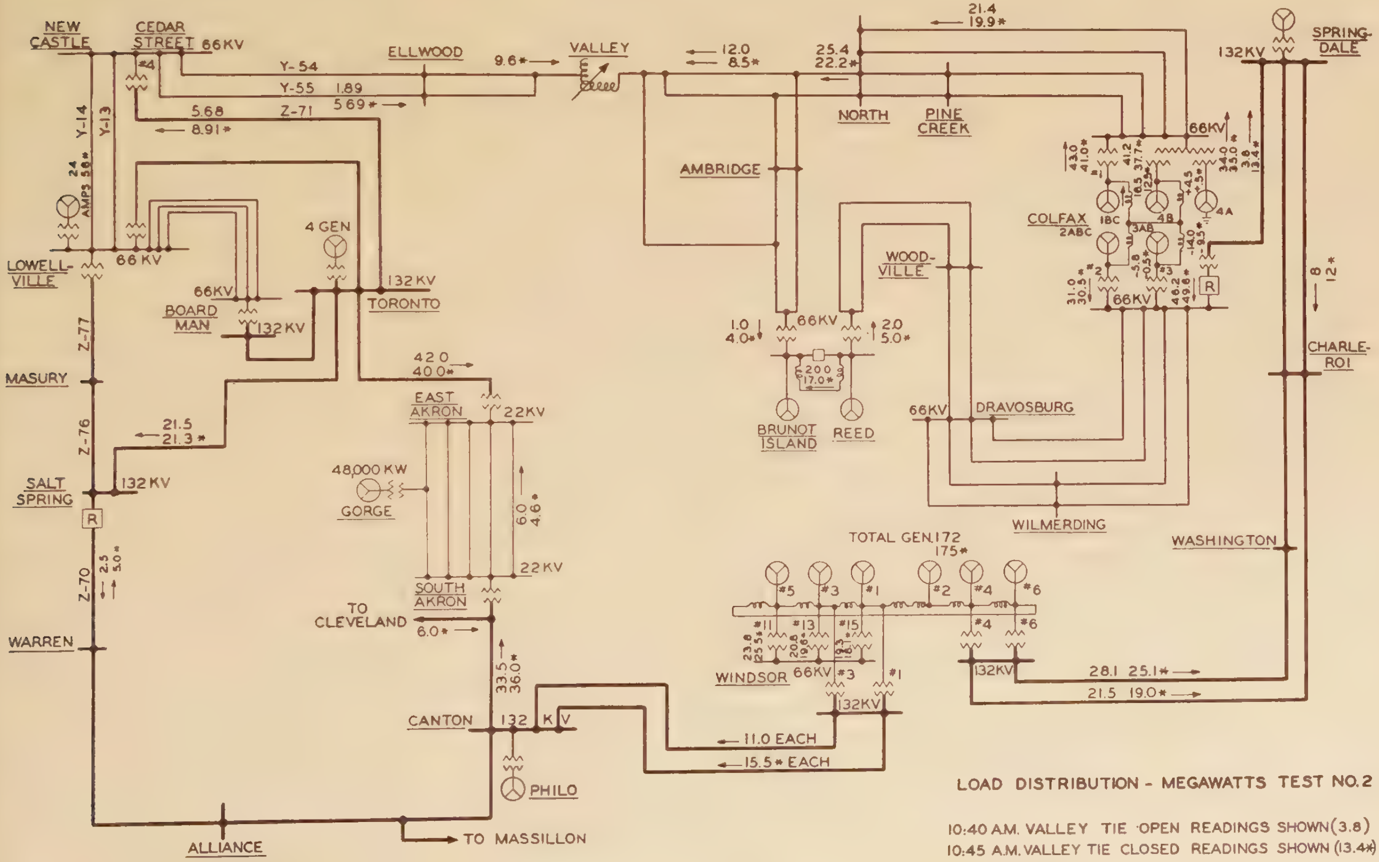


Figure 5. **Load distribution—megawatts**

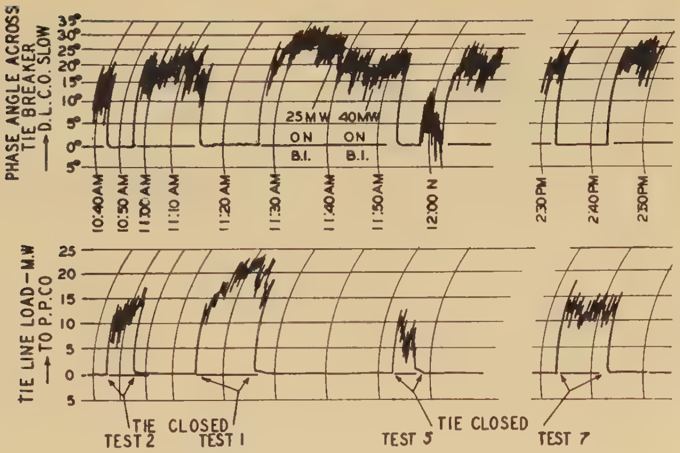


Figure 6. Relation between phase angle with tie open and power flow with tie closed

11 per cent, for individual circuits. Using this figure of 11 per cent applied to all circuits around the loop gives a phase angle variation curve for Valley with a standard deviation of 3.7 degrees. This compares favorably with the 3.8-degree standard deviation of the average curve on figure 7, taken from actual readings.

Future Phase Angle Conditions

The next step was to secure estimates by the various companies included in the transmission ring of the expected normal loads on their lines and transformers during heavy load periods after the installation of the scheduled generators at Reed, Springdale, Windsor (two 60,000-kw units), and New Castle. These loads were used to calculate the phase angles in the manner previously described, and it was found that the normal phase angle at Valley substation will be about 7.5 degrees.

Inasmuch as the future loads are only estimates, it is necessary to provide some margin for estimating errors and other changes which may occur. Assuming that there is one chance in ten of a forecasting error exceeding 25 per cent, a standard deviation of 15 per cent must be added to provide for this contingency. The combined standard deviation is the square root of the sum of the squares of the individual standard deviations, $\sqrt{15^2 + 11^2}$, which gives 18.6 per cent. This percentage was applied to the calculated future phase angles around the loop in order to obtain the standard deviation for each individual section. A value of 100 per cent was applied to the Colfax-Springdale tie and Windsor reactors, over which power may flow in either direction. The standard deviations thus determined were added numerically into groups, according to companies, since these circuits would be similarly affected by load shifts within each system. The root-mean-square of these latter figures gave the standard deviation for the angle at Valley as 6.4 degrees.

The resulting curve at the bottom of figure 7 shows, for example, that the angle will exceed 20 degrees about two per cent of the time, and will be less than −5 degrees about three per cent of the time. This curve gives a definite basis for applying a regulator with a fixed minimum range to compensate for an angle which has no fixed limits and which may vary over a very wide range.

Power Transfer

After setting the phase shifter to compensate for the natural angular difference, the tie line can be closed and no power will flow. If, then, it is desired to shift a block of generation from one system to the other, the phase-shifter setting must be changed to pass the power without permitting any of the power to circulate around through the other companies in the loop where it would very likely upset tie-line loadings.

The amount of phase shift needed to accomplish this power exchange may be readily determined by the process of superposition. For example: Suppose it is desired to transfer 20,000 kw from the Duquesne Light Company to the Pennsylvania Power Company by picking up 20,000 kw at the Colfax power station and dropping 20,000 kw at the Toronto power station. Regardless of the magnitude or direction of loads already existing on the intervening circuits, the net additional phase shift would be equal to that produced by transmitting 20,000 kw from Colfax to Toronto, assuming no other loads on the lines. In order to transfer this power without the phase shifter, Colfax would have to advance with respect to Toronto by this calculated angle. This, quite obviously, would cause power to flow also from Colfax to Toronto through the other systems in the ring. If, however, the phase shifter in the Valley tie is advanced by an amount equal to the calculated angle, Colfax and Toronto will not change their relative angular positions, and the only power flow will be the 20,000 kw from the Duquesne Light Company to the Pennsylvania Power Company through the Valley-Ellwood tie.

The phase angle produced by a given kilowatt load is not greatly affected by the power factor of the load on a system composed of transformers, reactors, and large capacity overhead lines, with consequent low ratios of resistance to reactance. It can be calculated approximately by the formula:

$$\text{Angle (degrees)} = \frac{(KW)\ (\text{Reactance})\ 0.057}{(KV)^2}$$

$$\text{Note: } 0.057 = \frac{1}{1000 \sin 1°}$$

The phase shift corresponding to the requirement of transferring 20,000 kw to the Pennsylvania Power Company, as described above, was found by calculation to be eight degrees (exclusive of *IZ* drop in phase shifter). Since the natural angle may be 20 degrees (Pennsylvania Power Company leading Duquesne Light Company), a total net range of 28 degrees would be necessary in order to be able to furnish 20,000 kw under all reasonable conditions. If the power factor of the interchange were 90 per cent lag, the above value of eight degrees would reduce to about seven degrees.

The phase angle required for shifting 20,000 kw at unity power factor between various points has been found by calculations and tests to be:

	Net Phase Shift Required* (Degrees)
Colfax and Toronto	8.0
Brunots Island and New Castle	6.5
Springdale and Windsor	3.5
Windsor and Philo	2.5
Toronto and New Castle	3.0
Colfax and Brunots Island	1.5

* Excluding regulator drop.

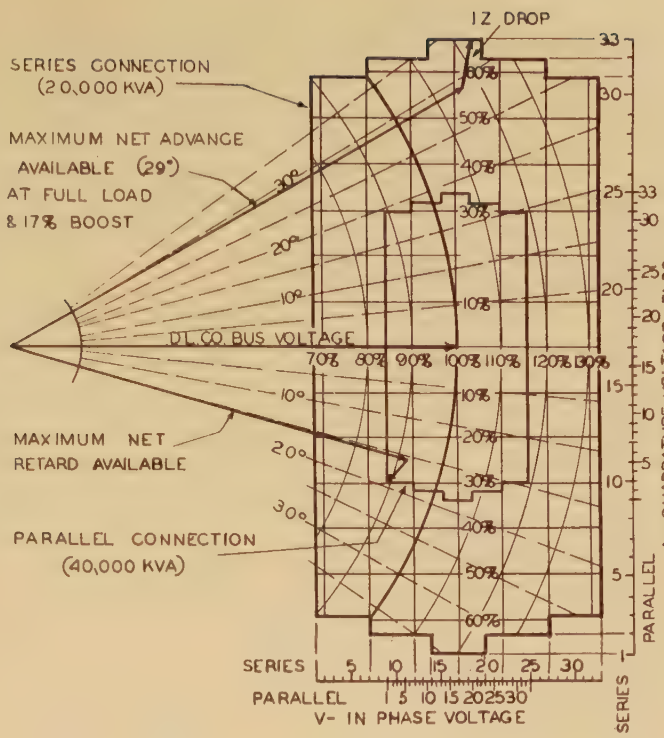
Selection of Phase-Angle Range

A regulator capable of handling 40,000 kva and having a net shift of 28 degrees with a 20,000-kva load would be very large and correspondingly expensive. Consequently, a close scrutiny was made of the requirements, with the result that a series-parallel arrangement was developed.

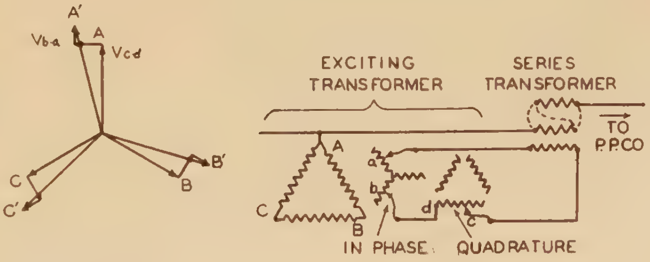
The 28 degrees is necessary for the condition of 20,000 kva to the Pennsylvania Power Company, which is the maximum requirement set up. However, since the Pennsylvania Power Company voltage is normally in advance of the Duquesne

Light Company voltage, a smaller phase shift is adequate to transfer power to the Duquesne Light Company. By the simple expedient of dividing into two parts the windings which carry the line current and providing a series-parallel switch, it was possible to reduce the rating of the regulator to 20,000 kva and 28 degrees net (33 degrees no load) on the series connection. By changing to the parallel connection, the carrying capacity becomes 40,000 kva, and the available phase shift of 15 degrees net (18 degrees no load) is adequate to transfer full load to the Duquesne Light Company under all reasonable conditions.

Figure 8. Regulator diagrams


IZ DROP
SERIES CONNECTION (20,000 KVA)
MAXIMUM NET ADVANCE AVAILABLE (29°) AT FULL LOAD & 17% BOOST
MAXIMUM NET RETARD AVAILABLE
PARALLEL CONNECTION (40,000 KVA)
D.L.CO. BUS VOLTAGE
30° 20° 10° 10° 20° 30°
70% 80% 90% 100% 110% 120% 130%
60% 50% 40% 30% 10% 10% 20% 30% 40% 50% 60%
SERIES 5 10 15 20 25 30
PARALLEL 5 10 15 20 25 30
V- IN PHASE VOLTAGE
A - QUADRATURE VOLTAGE TAPS
SERIES 5 10 15 20 25 30 33
PARALLEL 5 10 15 20 25 30 33

VOLTAGE DIAGRAM



VECTOR DIAGRAM SCHEMATIC DIAGRAM

The phase shift requirement for either company to take power through the Valley tie is materially reduced (about five degrees) if the company is at the same time taking power from other interconnected systems. This would be the normal condition during an emergency. Should conditions arise when the phase shift required is greater than the regulator capacity, the result is not serious. For a five degree shortage, the Valley tie will carry 3,500 kw less than desired and the other tie 3,500 kw more than the desired amount.

LOAD INCREMENTS

With 20,000 kw at unity power factor transferred as described above, the total phase shift would be 8 degrees through the systems, plus 5 degrees in the regulator itself, or 13 degrees. The load shift per degree is, therefore, computed to be about 1,500 kw when shifting between Colfax and Toronto. As shown by previous tests, and verified by calculation, an angle of one degree will send only 600–800 kw around the entire 300-mile loop. In this connection, the automatic load controller on the West Penn Power Company tie line at Colfax must be taken into account. A sudden insertion of one degree, such as by changing taps on the phase shifter, would circulate about 800 kw around the entire loop. This power, which would also flow through the West Penn tie at Colfax, would operate the tie line load controller, which would change the Colfax generation to return the tie line load to its original value. This would further increase the load change through the phase shifter after a brief interval to about 1,500 kw, corresponding to a transfer between the adjacent systems only. If the regulator steps were two degree each, the kilowatt change per step would be 3,000, which is not considered excessive, and is less than the normal power oscillations which occur continuously.

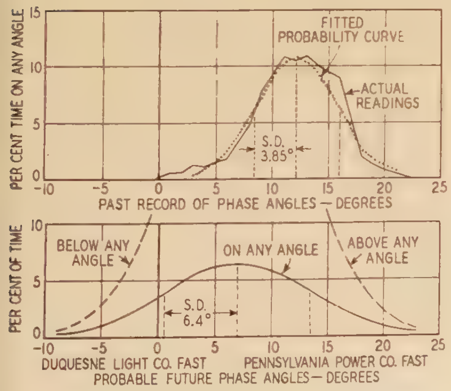


Figure 7. Natural phase-angle variation between Duquesne Light Company and Pennsylvania Power Company at Valley (no load on tie) Monday to Friday inclusive—8:00 a.m. to 8:00 p.m.

VOLTAGE REGULATING REQUIREMENTS

It is also necessary to provide an adequate range of voltage control in the regulating equipment. The normal voltage on the Duquesne bus at Valley is 63–65 kv. With a load transfer to the Pennsylvania Power Company of 20,000 kw at 0.8 power factor, the Duquesne bus would have a voltage regulation of 4.2 per cent and the regulator would, therefore, have to raise the voltage from approximately 61 kv to the required value of 71 kv, or 16 per cent net boost.

The normal voltage on the Pennsylvania Power bus at Valley is 65–68 kv. When supplying 40,000 kva at 0.9 power factor to the Duquesne Light Company, the voltage would be 60.5 kv. The desired voltage at Valley under this condition is 65.5, or a net boost of eight per cent (buck toward Pennsylvania Power Company).

Description of New Regulator

The single-line diagram on figure 8 shows the schematic arrangement of con-

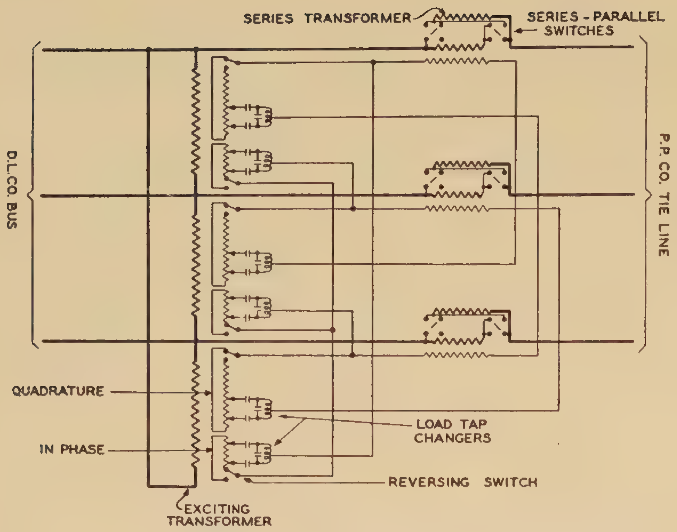


Figure 9. 66-kv regulating equipment—three-phase wiring diagram

nections, and figure 9 shows the simplified wiring diagram of the new phase-shifting transformer. The essential parts of this equipment are:

(*a*) *Exciting Transformer.* A 65-kv delta primary on a three-phase core, with two secondary windings, one for quadrature voltage and the other for in-phase voltage.

(*b*) *Series Transformer.* A three-phase core with one primary supplied from the exciting transformer and double secondary for 20,000 kva (series) or 40,000 kva (parallel) in series with the line. The change between the series and parallel connections is made with a hand wheel that can be operated from the ground level. This change cannot be made under load and, therefore, requires a five-minute interruption.

(*c*) *Two Load Tap Changers.* For quadrature and in-phase voltages, each with 33 steps, 16 on either side of neutral.

(*d*) *Two Preventive Autotransformers* for tap changing under load.

(*e*) *Fans* for increased rating. Rating 15,000/30,000 kva self-cooled and 20,000/40,000 with fans.

The voltage diagram on figure 8 shows the range of phase shift and voltage control available. In order to secure the net shift of 28 degrees on the 20,000-kva connection, a quadrature voltage of 67.5 per cent was needed. This would give 33.75 per cent quadrature voltage on the parallel connection. In order to utilize this and obtain an eight per cent boost when feeding toward the Duquesne Light Company (eight per cent buck toward the Pennsylvania Power Company) a 16 per cent buck was required as shown on the diagram. This determined the in-phase voltage required, although the resulting 32 per cent on the series connection is not all needed.

The quadrature tap changer can be made to operate automatically from a watt-meter in the tie line, in order to hold the load within any desired range.

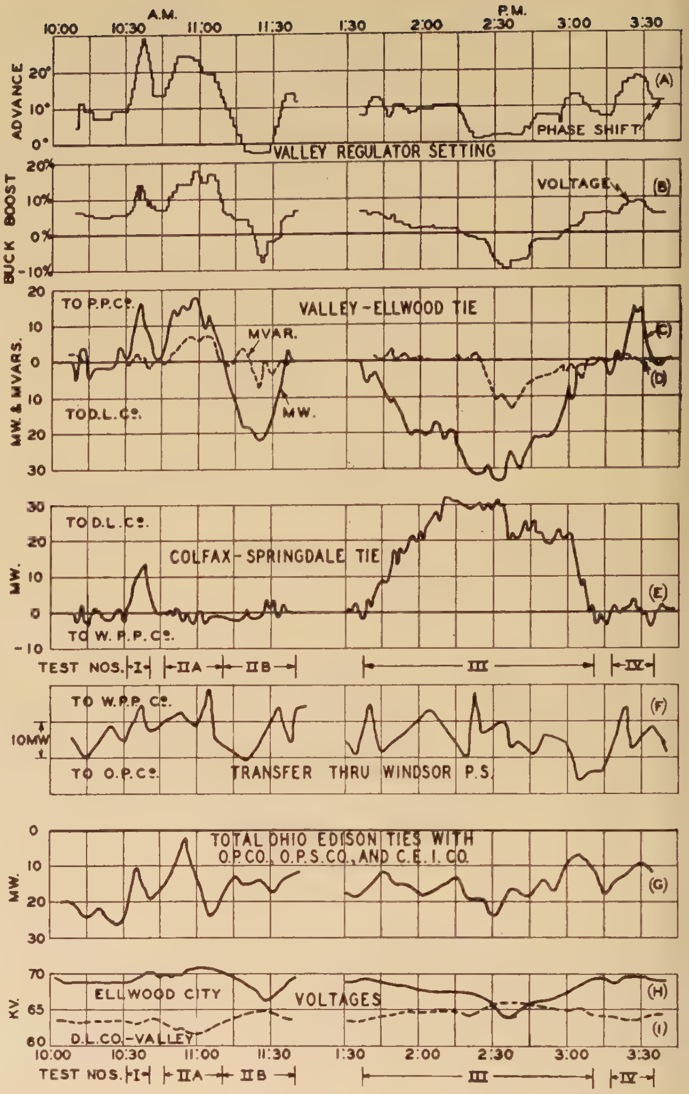


Figure 10. Results of load shifting tests

Results of Tests on Completed Installation

Arrangements were made to perform some load-shifting tests as soon as the regulator was available for service, in order to verify its ability to perform the functions for which it was designed. The load charts reproduced on figure 10 show the power interchange over the tie lines between the various systems making up the loop. The tests may be described briefly as follows:

Test I—20,000-Kva Connection, Power to Pennsylvania Power Company. With the automatic load control on the Colfax-Springdale tie inoperative, 15,000 kw were sent to the Pennsylvania Power Company by the phase-shifter control. The 15,000 kw flowed around the entire loop with practically no effect on generator output. Under similar conditions, during a previous test (before the phase shifter was installed) it had been impossible even by adjusting generator output and switching, to transfer any power directly from Valley to Ellwood substations.

The power flow per degree of phase shift was found to be 790 kw per degree. This is higher than the theoretical average value of 635 kw per degree due possibly to some unlooked for generator adjustments around the loop.

Test II-A—20,000-Kva Connection, Power to Pennsylvania Power Company. This was similar to test I, except that the automatic load control was operating on the Colfax-Springdale tie as it was in all tests except I. Figure 10 shows that no load change occurred on the Colfax-Springdale tie, Colfax picking up 15,000 kw of load equal to that transferred to the Pennsylvania Power Company. Curve *G*, however, shows that a large part of the 15,000 kw passed through Canton and South Akron and to the neighboring companies on the west.

The load shift at Valley proved to be 1,220 kw per degree, instead of 1,500 kw per degree, as had been calculated for a transfer from Colfax to Toronto, obviously because the load picked up at Colfax was dropped by power stations beyond the Ohio Edison Company system.

The 15,000 kw were transferred on regulator quadrature voltage tap *A*-28. Two more steps to tap *A*-30 would have increased the load to about 20,000 kw. The three remaining steps would have transferred the 20,000 kw even if the Pennsylvania bus voltage had been 18 degrees ahead of the Duquesne bus voltage (tie open) instead of 12 degrees as it was during this test. Furthermore, if all the load decrease had been made at the Ohio Edison Company plants there is no doubt that the 20,000 kw transfer could have been made in the face of a natural phase difference of 20 degrees, thus demonstrating that the phase-angle range provided is neither too small nor unnecessarily large to accomplish the established requirements.

Test II-B—20,000-Kva Connection, Power to Duquesne Light Company. About 20,000 kw were sent from the Pennsylvania Power Company to the Duquesne Light Company. In this case Colfax dropped 20,000 kw and most of it was picked up on the Ohio Edison Company plants, only about 5,000 kw coming through its ties to the west. The power shift in this case proved to be 1,530 kw per degree, which corresponds very closely with the predicted figure of 1,500 kw per degree for transfer between Colfax and Toronto. The method of analyzing this part of the problem is thus fully substantiated.

On this test, reactive power was transferred in order to adjust the power factor to the desired value. Each two per cent in-phase step transferred about 1,700 kilovars. Each 4.2 per cent quadrature step transfers about 3,000 kw between Duquesne Light Company and Ohio Edison Company. The greater effectiveness of the in-phase voltage is due to the fact that the only impedance to be overcome is between points where the voltage (magnitude) is held constant, which points are closer together than the generating stations between which power is being transferred. Synchronous motors and condensers also tend to maintain the voltage magnitude, but not the phase relation.

Test III—40,000-Kva Connection, Power to Duquesne Light Company. This test was run to demonstrate the ease with which desired amounts of power may be obtained by the Duquesne Light Company from both the West Penn Company and the Pennsylvania Power Company. A total of 64,000 kw was obtained, divided nearly equally between the two interconnections. With system conditions as they were at the time, very little phase shift was needed, but during emergencies such as would require this large amount of power, the phase-angle conditions would vary over a considerable range and most of the 15 degrees available would be needed.

Test IV—40,000-Kva Connection, Power to Pennsylvania Power Company. This test was performed to see how much power could be sent to the Pennsylvania Power Company with the limited range available on the parallel connection and the natural angle existing at the time (12 degrees). About 14,000 kw were transferred, using the full range of 18 degrees (no load). This average of 2,300 kw per degree is greater than on the series connection because the impedance of the regulator is only one-quarter as great. This reduces the total impedance between Colfax and Toronto by 33 per cent, which corresponds closely with the relation between 1,535 kw per degree and 2,300 kw per degree.

Conclusions

1. A regulating transformer to control phase angle as well as voltage magnitude is necessary in order to utilize successfully the tie line between Valley substation and Ellwood City.

2. The methods outlined herein for analyzing the characteristics of the interconnected system are entirely practical and accurate for determining the size and range of the in-phase and quadrature voltage control required.

3. The phase-shifting and voltage-regulating equipment, as installed, performed satisfactorily and gave positive and independent control of the kilowatt and reactive flow through the tie line under the desired conditions.

4. The use of a series parallel (20,000–40,000 kva) arrangement permitted a more economical solution of this problem where special load carrying and phase-shifting requirements had to be met.

5. The method outlined herein for expressing the future phase-angle variations by use of the probability theory is believed to be applicable to a variety of other problems of a similar nature.

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2. INTERCONNECTED POWER SYSTEMS, **Philip Sporn.** ELECTRICAL ENGINEERING, January 1938, page 16.

3. ECONOMIC STATISTICS (a book), **Crum and Patton.** A. W. Shaw Company, Chicago and New York City, page 199.

4. PROBABILITY AND ITS ENGINEERING USES (a book), **Fry.** D. Van Nostrand & Company, Inc., New York City.

Discussion

Robert Treat (General Electric Company, Schenectady, N. Y.): The considerable number of studies made, and of inquiries received for quotations on phase-shifting transformers over a period of years indicates that this subject has intrigued the imaginations of many utility engineers. The small percentage of such inquiries which have resulted in orders, however, indicates that the cost of solving the problem by this means has generally been considered disproportionate to the expected benefits. It would appear that most of the problems have been solved in a less expensive, perhaps also in a less satisfactory, manner.

This paper is of interest in that it describes one case in which a really competent and penetrating analysis showed the installation of a phase-shifting transformer to be economically justified. Operating experience appears to have confirmed the wisdom of the decision to proceed with the installation.

The information in this paper will be of great value to other engineers who are confronted with similar problems.

Philip Sporn (American Gas and Electric Service Corporation, New York, N. Y.): The type of transmission loop, described by Messrs. Lyman and North in this paper, is distinctly a product of the interconnection idea, as carried out by the various companies involved in this loop, including particularly the company with which I am associated. This problem of loop operation and inability to maintain complete control of power flow over individual portions of such loops is one that we are confronted with continually.

The authors have described a very thorough method of analysis of their particular problem, from the standpoint of both computations and field observations. The graphical representation of the actual and equivalent loop reactances as shown in figure 2 of the authors' paper is novel and helpful, and the application of probability theory to the selection of the range of control which can be economically justified, is also a sensible and practical means of approach. In fact, starting out on the premise that fairly complete control of power flow is necessary on an interconnection of this type in order to obtain the advantages of the interconnection, the authors have attacked and solved the problem in a sound and clever manner.

However, in the light of the experience we have gained in operating interconnected systems, I should like to raise a question as to the premise on which this entire study was based. At the outset it is stated that the interconnection is to be used only in case of an unusual emergency situation to provide an emergency source of power. I should like to ask why, as an emergency proposition, it would not have been possible to have taken care of the emergency by simply closing the switch at Valley, regardless of the particular phase-angle situation

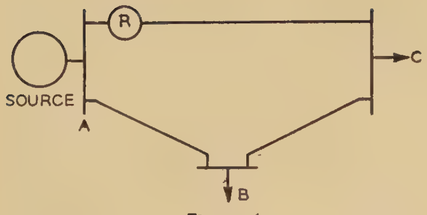

Figure 1

existing at the time, and allowing the power to flow in whatever direction and amount it chooses. Even though power did not flow in the direction and amount desired at that time, nevertheless, continuity of service would be maintained, and voltages would be upheld by the necessary exchange of reactive kilovolt-amperes, independent from the flow of power. After all, it is generally true in networks that power will flow over the path of least resistance, so that the simple closing of the switch without any attempt to force power to flow in any particular direction will generally result in the least over-all system losses from generating stations to loads. Of course, there may exist limitations in some cases, such as small capacity transformers in the loop which might be overloaded, but from the values of circulating load mentioned in the paper, it is my impression that this would not be the case on this particular loop.

For a permanent operating setup, the closing of a tie such as this, without phase-angle control, would undoubtedly introduce complications into the billing of the various groups physically connected in the loop. While this may appear insurmountable for permanent operation, it has been our experience that in most cases a solution is possible and that a great deal of effort to work out the problem on that basis is justified before resorting to phase-angle control. In other words, we believe that it is far better to let the power flow naturally and carry out such adjustment as may be called for in the billing arrangements rather than to resort to devices like phase-angle-control equipment which not only are a major expense in themselves but obviously decrease the reliability of the interconnections and in many cases serve only as a "bottle neck." In the particular case described, since it was established purely for taking care of emergency situations and was not intended for permanent operation, I would more than ever question whether the phase-angle-control solution is economically sound.

T. G. LeClair (Commonwealth Edison Company, Chicago, Ill.): The phase-shifter application described in the paper is an unusual one because the phase-angle range is so much greater than would normally be expected.

The discussion by Mr. Sporn might infer that phase shifters are not economically sound because in a closed network the power will follow the path of minimum reactance and, theoretically, the path of minimum loss. However, there are two conditions where phase shifters are of great economic value and where the general statement does not apply. One is the condition of two parallel lines in which the ratio of carrying capacity to impedance is not the same. For example, in Chicago we have two 66,000-volt cable circuits with nearly equal impedance, but with one having nearly twice the load carrying capacity of the other. A phase shifter is essential for this application.

The other necessary application for phase shifters is in large loops involving more than one company where the power flow must be controlled to meet arbitrary contractual agreements. In some cases, where one party to an interconnection is not co-operative, it may be cheaper to install a phase shifter than to pay penalties under a contract for not having maintained the correct line loading.

S. B. Griscom (nonmember; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors are to be commended for the thoroughness with which they analyzed the problem, and for their clarity in presenting the steps by which the required equipment ratings and characteristics were determined. The use of the probability theory to insure adequate but not excessive phase-angle range is particularly noteworthy.

Referring to figure 2, it is interesting to note that a very considerable portion of the total loop reactance is attributable to the bus reactors and voltage transformations at Colfax, Brunots Island, and Windsor. This would offhand lead to the conclusion that these connections are responsible for a large part of the required phase-angle shift. However, a review of table I shows that this is not the case, as under the expected loading conditions, the transfer of power through these elements is comparatively small. It is also very interesting to note that of the total quadrature range of the regulator, the major part is required to compensate for the cumulative phase angles generated around the loop, as compared to the nominal phase angles tabulated under "Power Transfer," required to shift 20,000 kw between various points.

The writer would like the authors' opinion as to the probable needs of the central station industry for combined phase-angle and voltage control for fields now commonly using step-type voltage regulators of nominal capacity, say 50- to 500-kva regulator size. For example, it seems to the writer that there must be frequent cases where load is fed as shown by figure 1 of this discussion. Load *C* is fed by two lines, one of which is tapped at *B*. Under these circumstances, the limiting load that can be delivered to *C* is reached when the line from *A* to *B* is fully loaded, whereas the direct line from *A* to *C* may be well under its maximum rating. A regulator at *R* will serve to force the necessary increment of load over the direct line to *C*, relieving the load on the line from *A* to *B*, and thus increasing the total load that may be served at *C*. In the simple case as illustrated, probably the emergency condition of one line out of service fixes the ultimate limit, but with other standby feeds to *C*, it would seem that dividing the load between the principal circuits in proportion to their capacity, a small investment in regulators would permit fuller utilization of a larger investment in lines.

It is possible to combine both phase-shift and voltage-ratio changes with a single regulating mechanism, provided that a fixed relation between them is permissible. In addition to the well-known 60-degree relationship, between the line and increment voltage, any other desired value may be obtained by proper design of the regulator.

The authors were able to make extensive tests on the interconnected system to obtain confirming tests of these calculations. These were supplemented by calculations projected to cover expected future conditions. While not particularly complicated, such calculations may prove quite arduous, particularly if a number of the lines have considerable resistance, and there are a large number of possible future conditions to be examined. In such cases, the work would be very much facilitated for the use of the a-c calculating board, such as the one used by the company with which the writer is connected. This board has been used on over 200 system studies since its installation eight years ago.

W. J. Lyman and J. R. North: The authors are indeed grateful for the interest shown in this subject by the discussions presented. It is worthy of note that no exceptions were taken to the method of approach and the manner in which the problem was solved. Particular notice was taken of the favorable reception accorded the use of probability analysis. This seems to reinforce other indications that the probability theory is coming to be more generally accepted as a method of approach with certain types of power system problems.

Mr. Griscom raised the question of the probable use of phase shifters in the future to balance loads on parallel circuits. The authors feel that this is a distinct possibility, and as described in Mr. LeClair's very interesting comments, the idea has already been applied. It would seem that, particularly in metropolitan areas where additional rights-of-way are becoming more difficult to obtain, there may be more pressure brought to bear to secure the maximum possible use of existing facilities. The example cited by Mr. Griscom is quite common, and in a few cases at least, reactors have been used to secure better load balance. However, where voltage regulation is a problem, the phase shifter might be justified by the amount of voltage control which could be obtained. In our opinion, such applications would, in general, involve larger sizes than those mentioned by Mr. Griscom. Mr. Treat's comments on the inquiries received on phase-shifting equipment may bear out the contention that more interest is being shown in this method of control and that it is at least being considered for the solution of a wider variety of problems.

Mr. Sporn's discussion of the economic aspects of the problem is quite pertinent. Naturally, the expenditure must be justified in one way or another. In this particular case it was largely as a result of the 1936 flood that it was decided to increase the interconnection capacity. Due to the great distances and the number of parties involved in the transmission loop it would not be possible to use the full rated capacity of both large interconnections without some form of power control. The phase shifter thus actually increases the effective interconnection capacity. Inasmuch as a new regulating transformer was required in any event to increase the tie line capacity, the phase-angle control was obtained for a reasonable incremental investment.

Field Testing of Bushings and Transformer Insulation by the Power-Factor Method

By I. W. GROSS
ASSOCIATE AIEE

I. Introduction

THE IMPORTANCE of maintaining the insulation on all parts of an electric system in good operating condition is fundamental with any power company today, particularly on such equipment as high- and medium-voltage bushings and transformers. The maintenance of such insulation requires some sort of periodic test to determine its condition, an exact location of faults, and requirements for reconditioning or replacing faulty parts.

Until the introduction of the power-factor method of insulation testing, the methods available were generally unreliable, uncertain, or of a type which destroyed the insulation if faulty or perhaps weakened it by excess voltage, even if normally good. The introduction by the Doble Engineering Company of a power-factor test set for field use some eight years ago made possible the practical testing of bushing insulation under service conditions. The further development of this test set, together with extension of its application to testing transformers and other equipment, and refinement in measuring technique and interpreting of results, has produced a highly satisfactory test device for determining the condition of high-voltage insulation in the field.

This successful development of field power-factor testing of insulation to its present state has been possible only through the closest co-operation between the manufacturer and users of the test set in the interchange of ideas, field records and technical data. Without such a procedure, progress would have been much impeded and the present usefulness of power-factor test application restricted. The equipment manufacturer has also lent his aid to this work, and in fact today at least two bushing manufacturers are power-factor testing new bushings as a routine test procedure, and one manufacturer has started power-factor testing high-voltage transformer windings.

Although the goal of complete elimination of all bushing, oil circuit breaker, and transformer failures in service probably never will be reached, the power-factor test method now available and in use by a large number of power companies has proved to be a useful tool in detecting faulty insulation prior to equipment failure in service. Reduced failures of equipment in service, decrease in cost of maintaining such equipment, and better service supplied by electric systems to their customers are the objectives of the periodic testing program of field insulation testing which has been in effect for the past five years on the system of the company with which the author is associated.

Figure 1. Light delivery truck, specially fitted to carry portable insulation test set and all accessories. A field test is being made on a 33-kv oil circuit breaker

II. Scope of This Paper

Power-factor testing of oil circuit breakers and their bushing insulation was tried out on the properties of the American Gas and Electric Company in 1929. The results were so satisfactory that a periodic test schedule was started on the same equipment in 1932 and extended to transformer insulation in 1934, and gradually to other miscellaneous equipment as the test work progressed. The results of much of this earlier work have been previously reported[1,3] in 1934.

Herein will be given:

1. An outline of our present test procedure.
2. General description of test methods used.
3. Our present test standards for judging insulation condition.
4. Summary of fault conditions found in bushings, power and instrument transformers, and oil circuit breakers, for the years 1932 to October 1937, inclusive, including some records on cork gaskets.
5. Discussion of results obtained.
6. Conclusions based on the results of some $5^1/_2$ years of actual field tests by the power factor method on equipment on the American Gas and Electric Company system.

It is outside the scope of this paper to discuss in detail bushing design as contributory to service faults, or to describe procedure for servicing equipment found faulty by test.

III. General Test Procedure

The test set, which has previously been described,[1] consists essentially of a 10,000-volt test transformer with means for adjusting the voltage and an instrument case containing wattmeter, voltmeter, and ammeter for obtaining readings of watts, voltage, and current. The power factor is readily obtainable in most cases

Figure 2. Rear view of test car showing instrument cases on top shelf, test transformer with control panel, oil test cup, and tool box on second shelf; and high-voltage test cable coiled in cylindrical pan on car floor

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[1] For all numbered references, see list at end of paper.

by one slide-rule setting. Other miscellaneous equipment, such as standard condenser, oil cup, test leads, guard circuit, safety switches, etc., comprise the balance of the equipment. All major test equipment is specially designed, and carefully shielded—an important feature required for use in the field.

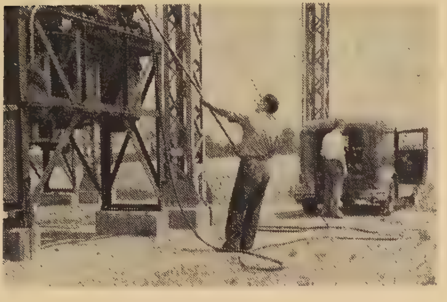

Figure 3. Field test of oil circuit breaker. The test man reads his instruments without removing them or the test transformer from the test car. The other man, standing on the ground, connects the test lead to the bushing with an insulated switch stick

In actual operation, the test equipment is carried in a light delivery truck as shown in figure 1. A view of the rear of the truck, with full door opening, is shown in figure 2. The interior of the truck has been specially fitted with shelves and partitions to hold the test equipment, not only rigidly in place during transit, but without being moved when testing is in progress. Figure 2 shows the instrument case on the top shelf, the test transformer, oil cup, and tool box on the middle shelf, and the 60-foot test lead coiled in a cylindrical container on the floor. A typical field test on an oil circuit breaker is shown in progress in figure 3.

The test schedule was first set up on a yearly basis. As the test work was extended each year to other equipment not contemplated when the schedule was first arranged, equipment has been tested every 18 months to two years instead of yearly as initially planned. At the present time we have three test sets in continuous use throughout the year.

All fault conditions found are immediately brought to the attention of the person in direct charge of maintenance, and major faults are recommended for immediate correction. Minor faults are pointed out, but are usually left until regular maintenance periods, or until next periodic test, according to the apparent importance of the fault and service conditions.

Copies of all field test records giving classification of faults according to severity, and recommending servicing procedure are promptly distributed to the person in charge of operation, to the Doble Engineering Company, and to the engineering department of the American Gas and Electric Service Corporation. Although the field-test men make the initial recommendations for servicing faulty equipment, subsequent triple review of the test data and recommendations are possible by the above procedure. Be it said to the credit of the test men, rarely has any exception been taken to their initial recommendations given at the time the tests were made in the field.

From the very start of this test program it was believed that the best results would be obtained by placing the test set in the hands of a technically qualified man, specially trained in this type of work, making tests continuously, and held highly responsible for the progress made and the recommendations given. Our experience bears out this belief. Such a man often detects fault conditions in the field which can easily be overlooked by adherence to an arbitrary set of power factor, watt loss, current, or other limits. Such limits are, however, essential as a basis of evaluating faults, although supplemental tests or inspections have frequently detected faults which would not have otherwise been found.

IV. Detailed Test Methods

In applying test voltage 10 kv is used unless this is above the safe limit of the equipment being tested or unless the charging current exceeds the range of the measuring instruments. If such conditions exist, the applied voltage is reduced to 5.0, 2.5, or 1 kv as required.

OIL CIRCUIT BREAKERS

The method of testing oil circuit breakers has previously[1] been described in detail. It consists essentially in testing each bushing separately, with the breaker open, and each tank separately (two bushings plus internal cross connection) with the breaker closed. It is usually unnecessary to disconnect the external leads to the bushing unless a fault condition is found. Evaluation of watts, power factor, and in some cases current (See V—"Classification of Faults" and table III) enable the classification of the insulation condition.

TRANSFORMERS

Testing the insulation of transformers by the power-factor method differs somewhat from the procedure followed in oil circuit breakers, first because physical separation of bushing from the internal insulation (winding) is usually not possible without opening the transformer tank (which involves extra labor), and second because it is often desirable to test the insulation of both windings of a transformer as well as their interwinding insulation. Also, another important feature that has to be considered is the relative large magnitude of watts loss and current in winding insulation as compared with those in bushings. This can easily obscure the fault in a transformer bushing unless it is disconnected and tested separately, or other means of test and analysis are used.

With instrument transformers such special test means and analysis have been

Table I. Test Procedure on Instrument Transformers
(See Figure 4)

Test Number	Meter Reading	Connections: Test To	Connections: To Ground	Connections: To Shield
1	$W_H + W_B + H_1 + H_2$	$H_1 + H_2$	L_1 L_2	
2	$H_1 + X^1$	H_1	L_1 or L_2	H_2
3	$H_2 + X^1$	H_2	L_1 or L_2	H_1

Table II. Test Procedure on Power Transformers
(See Figure 4)

Test Number	Meter Reading	Connections: Test To	Connections: To Ground	Connections: To Shield
1	$W_H + W_B$	H_1 and H_2	L_1 and L_2	
2	W_H	H_1 and H_2		L_1 and L_2
3	$W_L + W_B$	L_1 and L_2	H_1 and H_2	
4	W_L	L_1 and L_2		H_1 and H_2

successfully used to segregate winding faults from those in bushings. The procedure we have used is as follows: Referring to figure 4*A*, which represents a typical transformer, test voltage is applied simultaneously to the high voltage terminals H_1 and H_2, one terminal only of the low-voltage winding being grounded. A second test is now made with voltage on H_1, and H_2 connected to shield, other connections remaining the same. The third test is a repeat of test number two, with connections H_1 and H_2 reversed. The first test shows the over-all insulation condition of the transformer; the second and third tests (called cross checks) give, by comparison, the condition of each bushing. These three tests are outlined in table I. Where serious faults are indicated the bushings are separated from the winding and all tested separately. The insulation of the low voltage coil to ground is not tested as practical considerations have not yet indicated this is necessary.

In testing power transformers the loss in secondary winding insulation to ground must be measured and all winding losses evaluated. This has been done by the four tests outlined in table II. By proper combination of measured values the losses in, and power factor of, all three insulation paths can be obtained. The determination of the condition of the bushing insulation is not quite as simple here as with the instrument transformer on account of the relatively higher loss in the high-capacitance transformer windings. Several methods are available and have been used for determining the condition of the bushing alone without disconnecting it from the winding.

First, a comparison of the relative power factors of high, low, and inter-winding insulation which shows abnormally high loss insulation to ground usually indicates one or more faulty bushings connected to high-loss winding. Second, if the bushing is of the draw-lead type, the lead can be lowered inside the transformer tank by means of an insulating rod, and the bushing tested separately. A third method (hot-collar test) described below has also been successfully applied as an individual bushing test in some cases.

HOT-COLLAR BUSHING TEST

This test, which has recently come into use, is applied to bushings only, and consists of grounding the normally "hot" terminal of the bushing and applying the 10-kv test potential successively along the bushing at recesses between porcelain corrugations, and measuring the watts loss. Contact with the porcelain is made either through tinfoil wrapped around the entire porcelain circumference, or through a circular flat spring clamp which clips between the porcelain watersheds. This clip is energized on test, hence the name hot collar.

By this test a considerable number of faulty bushings have been detected, which upon examination were found to have such faults as cracks in the porcelain, porous porcelain, water (as much as a one-half cupful) inside the bushing at the top, and distributed moisture in the interior of the bushing. The test has always shown faults detected by the power factor test, and also faults such as the above, some of which the power factor test had not picked out.

SOLID INSULATION

Solid insulation such as wooden switch sticks, hot line sticks, and fibrous insulation such as insulating cylinders in bushings are being tested regularly by the power-factor test set. The standard test used is 10 kv between tinfoil or other metallic wrapping placed at three-inch intervals along the stick or cylinder, and insulation rating based on watts loss. While the technical justification why such a test is sound, is not at first clear, involving as it does creepage paths along the stressed surface of the insulation as well as the direct insulation path through it, it is a fact, however, that it is a practical and effective method of locating insulation defects in wood members and fibrous insulation.

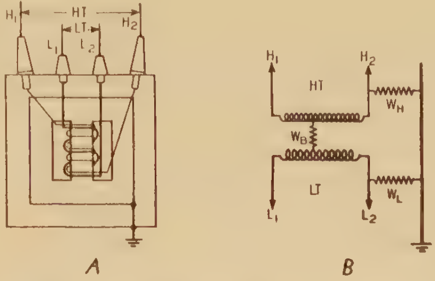

Figure 4. Insulation diagram of transformer

A—Typical transformer
B—Equivalent insulation diagram
HT—High-voltage side
LT—Low-voltage side
H_1 and H_2—High-voltage bushings and losses
L_1 and L_2—Low-voltage bushings and losses
W_H—Watts loss, high-voltage insulation to ground
W_L—Watts loss, low-voltage insulation to ground
W_B—Watts loss, insulation between high-voltage and low-voltage
X—Watts loss, $W_{B'} + W_{H'}$, where prime (′) equals the loss with one end of high-voltage grounded

Table III. Basic Rating for Insulation Quality From Power-Factor Field Tests
(Corrected to 20 Degrees Centigrade)

Apparatus	Type	Good (G)	Deteriorated (D)	Remove (R)	Remarks
		By Per Cent Power Factor			
Bushings	Comp. filled	Below 4.0	4.0 to 6	Above 6	
	Oil filled	Below 3.5	3.5 to 5	Above 5	Fibrous barrier
	Oil filled	Below 4.0	4.0 to 6	Above 6	Porcelain barrier
	Condenser	Below 3.5	3.5 to 5	Above 5	1-piece porcelain
	Condenser	Below 3.5	3.5 to 6	Above 6	Multi. shed
	Semicond	Below 4.0	4.0 to 7	Above 7	Also bulk type
Transformer-winding	C. T.	Below 3.5	3.5 to 6	Above 6	With bushings
	C. T.	Below 3.5	3.5 to 7	Above 7	Winding only
	Power and P. T.	Below 3.5	3.5 to 5	Above 5	
		By Watts Loss			
Oil circuit breakers	Most	Below 0.2	0.2 to 0.5	Above 0.5	Loss in tank
	33 Kv	Below 0.15	0.15 to 0.3	Above 0.3	Loss in tank
Herkolite cylinder	3-inch	Below 0.1	0.1 to 0.5	Above 0.5	Between bands
Wood bushings	3-inch	Below 0.1	0.1 to 0.5	Above 0.5	Between bands
	Comp. and cond.	Below 0.2	0.2 to 0.5	Above 0.5	Hot-collar test

ALLOCATION OF TROUBLE

Tests of this type are extremely helpful in definitely locating trouble, determining the cause, and applying corrective measures, once a piece of equipment such as a bushing or transformer has been found defective. The mere knowledge obtained by a test that shows equipment is faulty without allocating the trouble is only one step in maintaining electrical equipment in good operating condition. The tracing of the trouble to its source is just as important as finding a faulty piece of equipment, for the type and location of the trouble determines the nature of servicing required, even at times to the desirability of scrapping parts of or the entire equipment. This insight into insulation, the power-factor

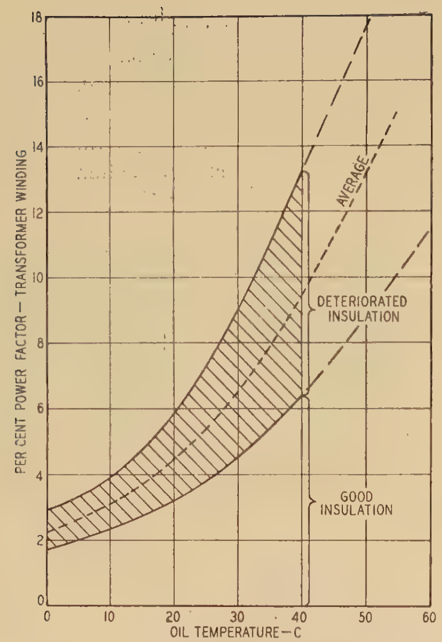

Figure 5. Power factor versus temperature correction curve for transformer winding (from field tests)

Table V. Power-Transformer-Bushing Faults Segregated as to Type; Summary of Four Years of Field Testing
(January 1934 to October 1937)

Type of Bushing*	Test	Number of Bushings Tested	Defective Number	Defective Per Cent	Remove Number	Remove Per Cent	Average—3 Tests Per Cent D	Average—3 Tests Per Cent R
A	First	1,182	31	2.6	46	3.9	2.5	2.8
	Second	772	15	1.9	12	1.6		
	Third	134	7	5.2	0	..		
B	First	875	77	8.8	58	6.6	8.7	5.0
	Second	447	28	6.3	8	1.8		
	Third	128	22	17.2	9	7.0		
C	First	2,515	100	4.0	141	5.6	4.0	5.5
	Second	1,399	52	3.7	76	5.4		
	Third	175	10	5.7	6	3.4		
D	First	2,132	22	1.0	26	1.2	0.8	0.9
	Second	1,071	5	0.5	6	0.6		
	Third	252	0		0			
E	First	1,025	19	1.9	11	1.1	2.0	1.3
	Second	722	13	1.8	11	1.5		
	Third	145	5	3.4	3	2.1		
Total	First	7,729	249	3.2	282	3.7	3.1	3.2
	Second	4,411	113	2.6	113	2.6		
	Third	834	44	5.3	18	2.2		

* Types of bushings refer to different basic principles of bushing design.

test set, with its direct readings of current and watts has been able to do with a high degree of certainty.

V. Classification of Faults

From the time the insulation in a piece of equipment leaves the factory in good condition until the end of its useful life (usually a period of years) it undergoes deterioration to a degree dependent on many factors such as duty in service, the elements, field servicing procedure, and faulty design. In the field testing of such insulation, by the methods described above, one of the immediate objectives is to determine, if possible, when the deterioration has become serious enough to warrant attention. The fault may be just starting and not serious but can be economically cured without allowing it to develop into a service failure. Again it may be so serious that immediate attention or even prompt removal from service is necessary.

Following this line of reasoning we have set up three classes of insulation as determined from test results. These are:

1. Good (*G*). No attention required.
2. Deteriorated (*D*). Not as good as new but not requiring special servicing until the next periodic test is made to check its condition.
3. Remove (*R*). Remove from service and recondition or scrap as conditions warrant.

Conforming to this procedure for rating insulation we have set up for use in our company "the basic rating for insulation quality" (table III) for the different types of equipment tested. Power-factor limits are given in the upper part of the table and watt-loss values in the lower part. In general, the power factor of good (G) insulation is shown 3.5 to 4% or less; deteriorated (*D*) insulation 3.5 to seven per cent; and remove (*R*) insulation above five to seven per cent.

Similarly, by the watts loss check the corresponding values range as follows: (*G*) 0.1 to 0.2 watt; (*D*) 0.1 to 0.5 watt; and (*R*) above 0.3 to 0.5 watt, again depending on the type of equipment tested.

As the power factor of insulation changes considerably with temperature the above power factor values are corrected to 20 degrees centigrade. A typical temperature power-factor correction curve for transformer insulation is shown in figure 5. The shaded area represents *D* insulation at various temperatures, which permits of ready allocation of insulation-test results obtained in the field. This set of curves was obtained from a

Table IV. Bushing Faults; Summary of $5^1/_2$ Years of Field Testing
(May 1932 to October 1937)

Test	Number of Bushings Tested	Defective Number	Defective Per Cent	Remove Number	Remove Per Cent
A. Power-Transformer Bushings (All kv ratings)					
First	7,729	249	3.3	282	3.7
Second	4,411	113	2.5	113	2.5
Third	834	44	5.3	18	2.2
Total	12,974	406	3.1 average	413	3.2 average
B. Power-Transformer Bushings (All kv ratings, excluding 15-kv and below)					
First	4,152	198	4.8	205	4.9
Second	2,477	84	3.4	57	2.3
Third	443	35	7.9	15	3.4
Total	7,072	317	4.5 average	277	3.9 average
C. Instrument-Transformer Bushings					
First	2,581	74	2.9	97	3.8
Second	2,145	70	3.3	73	3.4
Third	724	43	5.9	41	5.7
Total	5,450	187	3.4 average	211	3.9 average
D. Oil-Circuit-Breaker Bushings					
First	8,076	329	4.1	187	2.3
Second	7,302	287	3.9	114	1.6
Third	6,564	401	6.1	164	2.5
Fourth	1,758	83	4.7	38	2.2
Total	23,700	1,100	4.7 average	503	2.1 average
E. Spare Bushings (All kv ratings and types)					
First	1,084	76	7.0	86	7.9
Second	1,419	168	11.8	117	8.3
Third	1,089	143	13.1	110	10.1
Total	3,592	387	10.6 average	313	8.8 average

Table VI. Power-Transformer-Bushing Faults Segregated as to Voltage Rating; Summary of Four Years of Field Testing
(January 1934 to October 1937)

Bushing Kv	Test	Number of Bushings Tested	Defective Number	Defective Per Cent	Remove Number	Remove Per Cent	Average for 3 Tests Per Cent D	Average for 3 Tests Per Cent R
132	First	278	2	0.7	2	0.7	1.04	0.35
	Second	209	0		0			
	Third	88	4	4.5	0			
88	First	108	10	9.3	9	8.3	7.7	6.6
	Second	58	3	5.2	2	3.5		
	Third	0						
66	First	719	14	1.9	22	3.1	1.8	2.2
	Second	529	8	1.5	5	0.9		
	Third	0						
44	First	744	80	10.8	64	8.6	10.7	8.0
	Second	156	16	10.2	8	5.1		
	Third	0						
33	First	1,490	63	4.2	78	5.2	4.2	4.5
	Second	856	17	2.0	28	3.3		
	Third	336	31	9.2	15	4.5		
22	First	909	29	3.2	29	3.2	4.4	3.0
	Second	569	40	6.3	14	2.5		
	Third	0						
15 and less	First	3,477	51	1.5	78	2.2	1.5	2.3
	Second	2,034	29	1.4	56	2.7		
	Third	391	9	2.3	3	0.8		
Total	First	7,725	249	3.2	282	3.7	3.1	3.2
	Second	4,411	113	2.5	113	2.5		
	Third	815	44	5.4	18	2.2		

number of tests on actual transformers in service tested at several different oil temperatures, and represents the envelope of power factors of transformers rated (*D*).

In applying in the field the basic insulation ratings given in table III, considerable latitude is given the field-test engineer in assigning ratings where unusual or climatic conditions warrant. Important equipment, or comparatively wide variation in test values between similar pieces of equipment cause him, in some cases, to lower the limits given in the table. Again moist weather conditions and the like will sometimes cause him to boost the tabulated values slightly. Since the test engineer has been specially trained for this work, and is thoroughly acquainted with the problem, we believe the latitude permitted him in applying ratings is more than justified, and is far better than hewing close to an inflexible set of limits. Actual experience has borne out this policy.

VI. Test Results

The field test results summarized and discussed below include some $5^1/_2$ years of testing oil circuit breakers and four years of testing on transformers. Most of the breakers have had three periodic tests and some four tests; the instrument transformers two such tests, and the third is now being made; and the power transformers have had one test, some two, and a few three tests. In the following tables the designation "first," "second," and "third" test refer to the above periodic routine tests. For purposes of clarity the data have been generally segregated into and discussed under three groups: bushings, transformer windings, and internal faults for oil circuit breakers.

Bushing Faults

The summary of faults found in making over 45,000 individual tests on bushings is given in table IV. Bushings in power transformers average, for the three periodic tests, 3.2 per cent rated for removal (*R*); in instrument transformers 3.9 per cent; in oil circuit breakers (for four tests) 2.1 per cent; and in spare bushings 8.8 per cent. Bushings rated defective (*D*), but not sufficiently bad to be removed from service average for the same conditions and locations 3.1 per cent, 3.4 per cent, 4.7 per cent, and 10.6 per cent, respectively. One point of interest in the foregoing figures is the fact that (*D*) and (*R*) faults are roughly of the same order of magnitude except for oil-circuit-breaker bushings where the (*D*) faults are slightly over twice the

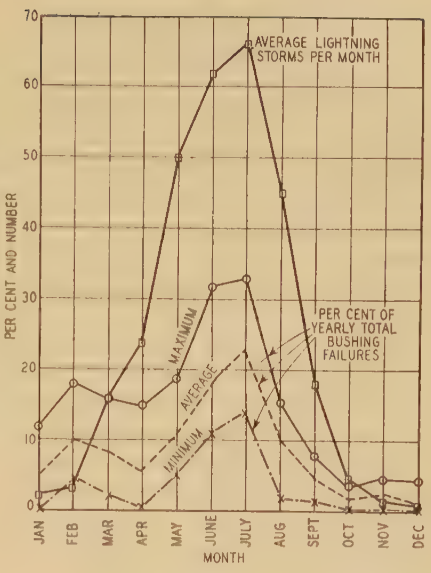

Figure 6. Bushing failures versus lightning frequency, 1932–37

Table VII. Power-Transformer-Winding Faults Segregated as to Kilovolts Rating; Summary of Four Years of Field Testing
(January 1934 to October 1937)

Transformer Kv	Test	Number of Transformers Tested	Defective Number	Defective Per Cent	Remove Number	Remove Per Cent	Average for 3 Tests Per Cent D	Average for 3 Tests Per Cent R
132	First	179	7	3.9	1	0.56	4.5	0.27
	Second	133	7	5.3	0	0		
	Third	65	3	4.6	0	0		
88	First	52	8	15.2	0	0	16.9	0
	Second	25	5	20.0	0	0		
	Third	0						
66	First	296	26	8.8	5	1.7	8.8	2.3
	Second	227	20	8.8	7	3.1		
	Third	0						
44	First	338	66	19.5	9	2.6	19.1	2.2
	Second	70	12	17.1	0	0		
	Third	0						
33	First	634	107	17.0	28	4.5	19.5	5.0
	Second	344	76	22.0	21	6.1		
	Third	131	34	26.0	7	5.3		
22	First	326	66	20.2	9	2.8	22.0	2.9
	Second	189	47	24.8	6	3.2		
	Third	0						
15 and below	First	83	11	13.3	3	3.6	14.5	3.2
	Second	39	6	15.4	1	2.6		
	Third	13	1	7.7	0	0		
Total	First	1,908	291	15.2	55	2.9	16.1	3.1
	Second	1,027	173	17.0	35	3.4		
	Third	209	39	18.6	7	3.4		

(*R*'s). It is suggested that this higher ratio of (*D*) to (*R*) faults in oil circuit breakers may be due to slight deposits of carbon at the bottom end of breaker bushings as a result of arc interruption, and that usually the bushing is freed of the fault in normal breaker maintenance before the fault develops to an (*R*) condition.

Another point of interest shown in table IV is that total faults, both (*D*) and (*R*), do not progressively increase or decrease in any of the bushing groups from the first test period to the second, third, or fourth test. This clearly indicates that bushing deterioration is gradually taking place, and that removal of faulty bushing during one test period does not preclude bushing faults developing before the next test period some $1^1/_2$ years or so later. In fact bushings rated (*R*) on the second, third, and fourth tests have often been found (*G*) or good on the previous test; all (*R*) bushings have not progressed from a previously found (*D*) fault.

The high percentage of faulty bushings in the spare group is due to two causes: first, the fact that some bushings known to be faulty and ready for the process of reservicing were included in this group; and second, normal storage methods generally used for spare bushings is not particularly helpful in retaining such bushings in first class conditions.

A further analysis of power transformer bushing faults according to bushing type is given in table V. The data represent some 13,000 tests on bushings. The (*D*) conditions range from 0.8 per cent to 8.7 per cent and the (*R*) faults from 0.9 per cent to 5.5 per cent on the average for all three periodic tests. Here again no well-defined tendency is shown for the faults to decrease, stay constant, or increase with each successive test, in any particular type of bushing. It should be definitely pointed out that the data presented in this table should not be construed or interpreted as a quality index of bushings manufactured today. It does indicate, however, the frequency and severity of faults on all bushings as a group on the system involved, and shows clearly where maintenance work should be concentrated to reduce bushing failures.

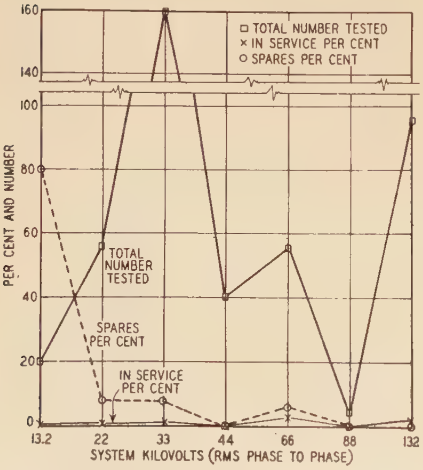

Figure 7. Effect of transformer kilovolts on power-transformer-winding faults (R) conservator and nonconservator type; 110 banks (440 transformers)

Table VIII. Internal Faults in Equipment
(May 1932 to October 1937)

Test	Number of Transformers Tested	Defective Number	Defective Per Cent	Remove Number	Remove Per Cent	Average for 3 Tests Per Cent D	Average for 3 Tests Per Cent R
Winding Faults—Power Transformers							
First	1,908	291	15.2	55	2.9	16.0	3.1
Second	1,027	173	17.0	35	3.4		
Third	209	39	18.6	7	3.4		
Winding Faults—Instrument Transformers							
First	1,502	451	30.1	113	7.5	35.0	7.8
Second	1,283	497	38.6	98	7.6		
Third	407	163	40.1	36	8.9		

Tank Faults—Oil Circuit Breakers

Test	Number OCB's Tested*	Defective Number	Defective Per Cent	Remove Number	Remove Per Cent	Average for 4 Tests Per Cent D	Average for 4 Tests Per Cent R
First	1,346	304	7.5	65	1.6	6.2	1.7
Second	1,217	178	4.9	57	1.6		
Third	1,097	210	6.4	67	2.1		
Fourth	293	41	4.7	10	1.1		

* Multiply by three to obtain number of tanks.

The power-transformer-bushing faults have further been segregated as to voltage class in table VI. The high-voltage 132-kv bushings show the lowest percentage of faults, the 66-kv and 13.2-kv class next lowest and the medium-voltage group the highest. The rather high percentage of faults shown for 88-kv bushings is due largely to the fact that most of these bushings are of old and obsolete designs.

BUSHING FAILURES

It is unfortunate that accurate records are not available to show the decrease in bushing failures over the system before and after the test program was adopted. However, from the rather scattered records available from 1932 to 1937, it is interesting to note how closely the frequency of bushing failure and lightning storms coincide throughout the year. Such a correlation is shown in figure 6. Except for the first three months of the year failures and storms practically increase and decrease together. The relatively high rate of bushing failures in the first three months has been attributed to weather conditions wherein maximum temperature changes exist, frequently associated with the presence of moisture which is an ideal combination of circumstances to open up weak bushing gaskets and permit the entrance of moisture into the bushing. In fact the major number of bushing failures appear to result from the presence of moisture within the bushing.

INTERNAL AND WINDING FAULTS

Faults found in windings in some 2,000 tests of power transformers are shown in summary form in table VII. The faulty conditions have been grouped under transformer voltage rating and further broken down to show the trend of faults from one test period to the next. Like the transformer bushings, the winding faults are lowest in the high-voltage windings, lower but still high in the low-voltage class, and highest in the medium-voltage ratings. While the (*R*) faults are in the same general order as bushings, it should be noted the (*D*) faults are much higher, ranging from 4.5 to 22.0 per cent. Again, there is no characteristic trend to prevent the occurrence of faults in other transformers of the group from one test period to another, although the faulty conditions found have been removed prior to the next test.

Internal faults in instrument transformers and in oil-circuit-breaker tanks are shown in table VIII, together with a condensed summary of power transformer winding faults given in more detail in table VII. One important fact, which correlates with the failure operating record, is the high percentage of (*R*) and (*D*) faults shown in instrument transformer windings, namely 7.8 and 35.0 per cent average for three tests.

Faults in oil circuit breakers show low (*R*) conditions and fairly high (*D*) percentages. This may be explained in part, at least, by the more frequent servicing of oil circuit breakers than transformers. Although the (*D*) faults are high they are apparently removed by sufficiently frequent periodic servicing before they develop into (*R*) faults.

Transformers in Service and Spares

An analysis of power-transformer-winding faults on the basis of transformer voltage and age is shown in figures 7 and 8. These data were taken from conservator and free-breathing single-phase transformers operated in banks of three units with one spare. So long as the transformers are in service both types indicate relatively few (*R*) conditions irrespective of voltage rating; but the (*R*) conditions slowly increase with transformer age.

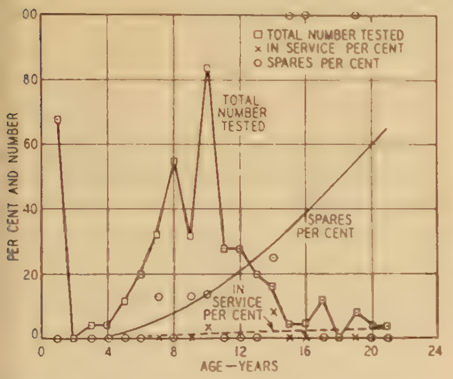

Figure 8. Effect of transformer age on power-transformer-winding faults (R) conservator and nonconservator type; 110 banks (440 transformers)

In the spare units, however, a high percentage of (*R*) conditions is indicated in the 13.2-kv class which drops abruptly in the 22-kv class and then slowly decreases as the voltage increases. On the basis of age, the spare units show a large increase in percentage of (*R*) faults after some six years, showing some 25 to 50 per cent faulty units in the age range from 15 to 20 years. Most of these spare units have from the start been held as spares and only put in service as occasion required.

Faulty Gaskets

Faulty and deteriorated gaskets have generally been recognized as one of the major sources of bushing troubles. Some information has been collected in the field on this gasket problem along with the power-factor test work and is presented here.

Figure 9 shows the condition of some 376 bushing gaskets physically inspected in the field on compound filled bushings. These have been rated (*G*), (*D*), and (*R*) with the same understanding as to terminology as applied to bushing faults. It will be noted that after some five years, the gaskets begin to grow faulty at an alarming rate. At the end of some 15 years, 60 per cent of the gaskets are in an (*R*) condition and 30 per cent in a (*D*) condition. Such a record as this leads us to believe that the older type of cork, at least, should not be depended upon in compound filled bushings much longer than five to seven years at the most.

Summary of Power-Factor Tests on Oil Circuit Breakers and Transformers

A composite summary of oil circuit breakers and transformers tested and the average number of faults found during the $5^1/_2$ years of testing is given in table IX. Several interesting points are brought out in the tabulation: First it is shown that there are 1.52 times as many faulty (*R*) conditions in power-transformer bushings as in oil-circuit-breaker bushings, and second, instrument-transformer bushings have 1.84 times as many similar faults. The (*D*) faults are shown, on the same basis, as 0.66 and 0.72 times those in oil circuit breakers, respectively.

An analysis of internal faults (*R*) shows ratios of 1.95 and 4.8 for power-transformer and instrument-transformer windings, respectively, compared with oil-circuit-breaker-tank faults. The corresponding ratios for (*D*) faults are 2.6 and 5.6. A study of this table IX indicates clearly where the highest percentage of faults exist.

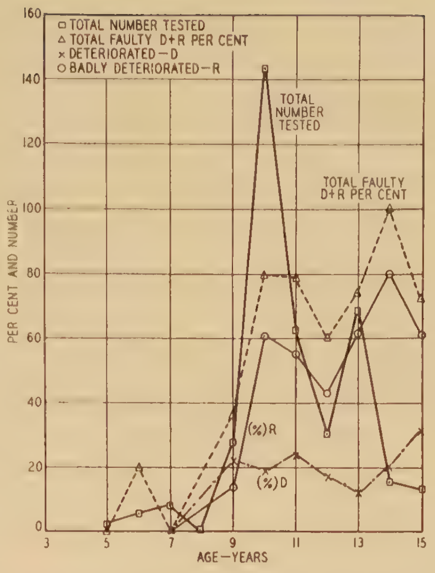

Figure 9. Faulty cork gaskets in compound-filled bushings found by physical inspection; 376 gaskets inspected

Table IX. Summary of All Equipment Power-Factor Tested
(May 1932 to October 1937)

Equipment Tested	Number of Tests	Defective		Remove	
		Number	Per Cent	Number	Per Cent
Oil Circuit Breakers	3,950				
Tanks	11,850	733	6.2	199	1.6
Bushings	23,700	1,100	4.7	503	2.1
Power Transformers	3,144				
Windings*	3,144	503	16.0	98	3.1
Bushings	12,974	406	3.1	413	3.2
Spares in storage**	410	125	30.5	82	20.0
Instrument Transformers	3,192				
Windings*	3,192	1,111	34.8	247	7.7
Bushings	5,450	187	3.4	211	3.9
Spares in storage**	242	51	21.0	48	19.8

* All windings of a transformer classed as *one winding*.
** Rating based on over-all condition—winding and bushings.

Fault Distribution by Companies

As the data of fault conditions of insulation presented above were obtained from six different companies, operating in different sections of the country, under different climating conditions, and various requirements, the question may well be asked: "How do the fault conditions compare between the different companies?" A comparison of results on this basis is given in table X. Of the some 60,000 tests reported above, the (*D*) faults ranged from 3.0 to 8.3 per cent, averaging 6.7 per cent; and the (*R*) faults ranged from 0.8 to 3.5 per cent, averaging 2.8 per cent.

It is therefore evident that faulty insulation conditions, both (*D*) and (*R*) faults run in the same general order in all six companies except company (*F*). In this one case it is known that new equipment and a large concentration of the tested equipment in power stations, where maintenance is inherently closely watched, seems to account for the lower fault record.

Table X. Summary of Power-Factor Tests in All Companies
(Including Oil Circuit Breakers, Transformers, and Bushings)
(May 1932 to October 1937)

Company	A	B	C	D	E	F	Total
Total Tests—bushings, oil circuit breakers, tanks and transformers	18,911	6,347	2,925	8,618	19,829	3,685	60,315
Number of equipment:							
Rated *D*	1,580	508	173	694	976	110	4,041
Per cent rated *D*	8.3	8.0	5.9	8.1	4.9	3.0	6.7
Number of equipment:							
Rated *R*	613	155	101	250	523	29	1,671
Per cent rated *R*	3.2	2.4	3.5	2.9	2.6	0.8	2.8
Number of equipment:							
Rated *G*	16,718	5,684	2,651	7,674	18,330	3,546	54,603
Per cent rated *G*	88.5	89.6	90.6	89.0	92.5	96.2	90.5

Equipment found good (*G*) ranged from 89.0 to 96.2 per cent with an average for all six companies of 90.5 per cent.

VIII. Summary and Conclusions

From the data presented above, and other related testing work carried on in the field during the past six years, the following conclusions appear justified:

1. The power-factor test method of determining the insulation quality of high-voltage equipment in the field has proved a most useful and practical tool in permitting a higher grade of apparatus maintenance and in reducing service failure of such equipment.

2. The type of power-factor test set which has been used has proved an accurate, rugged, and reliable instrument in use. The particular features of this set which permit of direct reading of current and watts loss have been particularly helpful in locating faults in equipment shown defective by the over-all power factor determination.

3. It is considered highly desirable, for best results, that the test set be placed in the hands of a thoroughly trained experienced test man who is familiar with the insulation problem, and one who has considerable knowledge of equipment design, maintenance and operation.

4. Insulation faults develop in all types of equipment such as bushings, transformers, wood insulation, and oil regardless of equipment design as it exists today. These faults may develop critically within test period intervals of 18 months to two years, as shown by the experience cited above, and appear, in a few cases, to develop to a lesser degree in a shorter period of time. Periodic testing, therefore, is necessary if a high standard of insulation is to be maintained.

5. Critical insulation faults found on successive tests are not always developments of (*D*) conditions found on the previous test; they often appear in equipment that previously tested good (*G*).

6. Faulty insulation is less frequent in new equipment, but may be expected to develop to a degree warranting some concern within a period not longer than some five years, after which constant periodic checking, or testing, seems desirable if critical faults are to be minimized.

7. Most faulty equipment so far found can be reconditioned with a reasonable amount of labor and expense, and many costly failures thus avoided, if prompt attention is given to (*R*) faults.

8. The classification of insulation faults on a power factor and/or watts loss basis as given in table III above, and servicing them on this basis has proved a reasonable and practical method of greatly reducing service failures on the equipment tested.

9. Insulation faults requiring prompt attention, which develop under service conditions in oil circuit breakers and transformers, as found by our experience, range, on the average over several years, as follows:

Oil circuit breakers, including bushings	1.6 to 2.1 per cent
Power - transformer windings, including bushings	3.1 to 3.2 per cent
Instrument transformer windings, including bushings	3.9 to 7.7 per cent
Bushings in the above three items	2.1 to 3.9 per cent

10. The economic value of this test work in system maintenance is unquestionable, although it is difficult to express the savings effected in money value done.

IX. Acknowledgments

The author wishes to acknowledge the careful and painstaking field work of Mr. E. W. Whitmer of the American Gas and Electric Service Corporation, and of Mr. F. D. Brook of the Appalachian Electric Power Company in obtaining the field records, and their help in preparing the summarized data in the paper.

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Discussion

H. L. Cole (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): Mr. Gross has made a valuable contribution to the art of power-factor testing in presenting the large amount of data given in the paper. This is particularly true with respect to tests on terminal bushings. The value of power-factor testing of bushings is well established.

In connection with the table of "basic rating for insulation quality," it is noted that a correction is made to bring the measured values to an equivalent 20-degree-centigrade figure. It is thus recognized that temperature plays an important part in the rating of the insulation.

For several years we have recommended lower power-factor limits for bushings operating in hot oil, as on power and distribution transformers. For instrument transformers and breakers, somewhat higher limits are safe. I believe that a basic rating should make a distinction between bushings operating in hot oil and those in oil at ambient temperature.

L. Wetherill (General Electric Company, Pittsfield, Mass.): This paper brings out the advantages of having power-factor tests made by men who are well qualified to exercise judgment in the interpretation of data obtained in the field, making it possible to take immediate action and avoiding the necessity for rigid adherence to a system of arbitrary limits. We believe that the acceptance of this viewpoint is one of the reasons why satisfactory results have been obtained from field power-factor tests on bushings, and doubtless it will prove even more beneficial in connection with other types of apparatus in which the designs are less standardized.

A question is raised regarding the theoretical justification for power-factor tests made on fibrous materials, such as insulating cylinders, between electrodes placed three inches apart on the outside surface. Our experience has been that measurements of this nature offer a particularly sensitive method of detecting the presence of moisture. It would seem that a very small trace of moisture present in fibrous or laminated materials tends to produce a marked change in electrical loss characteristics when the stress is applied parallel to the laminations. If we were dealing with large masses of insulation it would be found that the power-factor measurement obtained with the voltage applied parallel to the laminations would be the most sensitive method of detecting small traces of moisture. In materials such as cylinders, it is rather difficult to make a power-factor test in which the stress is entirely parallel to the laminations, since a test between the ends of a cylinder would permit the stray capacitance to mask the power factor of the cylinder. The method of test used by Mr. Gross, namely, the application of voltage between the electrodes placed three inches apart on the outside of the cylinder, appears to be the most practical method of making a test in which the stress is applied principally parallel to the laminations. It would seem, therefore, that there is adequate theoretical justification for the use of this test in addition to the support which has been afforded by practical experience.

The curves of figure 6 showing the correlation between failures and lightning storms is quite interesting, but the disagreement of the two curves during the early part of the year suggests that it might be well to examine the correlation between failures and humidity or precipitation. We have known for some time that moisture and lightning were the chief causes of failure, but the curves of figure 6 seem to suggest that both factors in combination are involved in the majority of cases.

Mr. Gross states that the data in his paper are not representative of the bushings which are now being manufactured. A lapse of five to seven years is required before field-test data and experience obtained on a given design begin to acquire great significance. I believe, however, that evidence obtained from developmental tests gives us excellent reason for believing that bushings as now manufactured, will in most cases be found markedly superior to those which were manufactured in past years before the present extensive body of field experience was accumulated.

L. B. Chubbuck (Canadian Westinghouse Company, Hamilton, Ont.): Our company apply routine power-factor tests to all new high-voltage bushings and have carried out extensive field power-factor tests across Canada. We fully agree with Mr. Gross as to the value of field testing, and have found may cases of apparatus showing poor power factor that after cleaning or other minor repairs returned to good operating condition.

During this discussion the point was raised as to whether power-factor tests on high-voltage apparatus should not be made at operating voltage, rather than at approximately 10,000 volts. We have equipped a power-factor bridge with an external condenser of 150 micromicrofarads designed for 100 kv at atmospheric pressure, and up to 187 kv with increased pressure. Due to ionization losses we find power factors obtained with the high-voltage bridge usually run considerably higher than with the standard bridge.

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): In making use of field power-factor data obtained on transformers Mr. Gross is exploring a field in which the complexity and difficulties will undoubtedly be considerably greater and more numerous than those which were encountered when the use of field power-factor measurements on bushings and circuit breakers was being developed. The greater variety of types and designs of transformers will necessarily make the interpretation of the data a task which will call for a high degree of judgment, and it appears that Mr. Gross is making the right approach in this matter.

It would appear that the usefulness of field power-factor measurements on transformers can only be established by the creation of a considerable quantity of operating experiences and test data judiciously interpreted. The information given in this paper should prove significant and suggestive, both to operators and to manufacturers. We would like to raise a number of additional questions which Mr. Gross may be in a position to answer.

1. In tables VII, VIII, and IX data are shown regarding the number (or percentage) of power-transformer windings which were deemed to be in a condition requiring removal from service. It would be desirable to know whether or not subsequent examination verified the presence of definitely undesirable conditions in approximately all of these cases or if there was an appreciable number of cases in which subsequent examination disclosed no defect.

2. In cases where definite defects in transformers windings were found after removal from service, is it possible to indicate the approximate proportion of cases of undesirable conditions falling into the following classes?

A. Presence of water in insulating oil.
B. Presence of water in solid insulating materials.
C. Deterioration of oil.
D. Deterioration of solid insulating materials.
E. Failure or breakdown.

3. Were there any other major causes of defects not covered by the previous question?

4. In the case of transformers removed from service, was it found possible to carry out a reconditioning permitting them to be restored to operation, and if so, what type of reconditioning was used?

5. In how many cases were repairs necessary other than reconditioning mentioned in (4)?

6. Table IX indicates a higher percentage of transformers for which removal was recommended under spares than under active units. Were the types of unsatisfactory conditions found in the spare units essentially the same as those found in the active units, or was there a greater preponderance of a different type of unsatisfactory condition in the spare units as compared with the active units? Were spares modern transformers or old transformers?

It is, of course, well known that high power factor does not always mean low dielectric strength of insulating materials. For any given material or configuration there are, however, normal power-factor characteristics, and any wide deviation from these normal characteristics is indicative of some physical change which usually deserves investigation, and quite possibly correction. Increases in power factor may be caused by chemical contamination, oxidation of oil, or by absorption of moisture. For many types of apparatus it would appear that operating experience has shown that appreciable increases in power factor are usually related to the third of the three causes listed above. This would appear to be a sound justification for the use of field power-factor testing, when, as recommended by Mr. Gross, adequate judgment is exercised in interpretation of the data.

It would be interesting to know if Mr. Gross during his investigation has had an opportunity to obtain any relative power factors on a given transformer or transformers. Our experience in measuring insulation resistance of transformer windings leads us to believe that, when working with insulation structures having such a variety of configurations, relative power factors may be more valuable than actual values.

We are in sympathy with any method which aids in detecting incipient faults in transformers. At the present time power factor measurement appears to give promise, although it will need to be developed with considerable care in order to avoid the possibility of drawing false inferences by comparison of readings obtained on units of different design and characteristics.

Harold Goodwin, Jr. (Wyncote, Pa.): The paper is very valuable in making known the results of a large number of tests on particular types of insulation by a particular method. The factors obtained can be used in further practical applications of the method. But the mere presentation of the results raises in the mind the questions: "Why?" "How does the current flow to give the results indicated by the instruments?" The oral discussion and the contributions by some specialists on cable also indicated these questions. The cable specialists might join in the search very diligently as they may get some help for their problems from the solution of the bushing problem, just as I hope the bushing specialists may get some help from the telephone engineers, as I shall point out below.

Compound-filled bushings which have failed in service or which have tested defective and been removed and tested to destruction have, from my observation, generally indicated one basic type of failure: the compound has tended to separate from the porcelain rain shield, leaving a fissure that is likely to be somewhat conducting due to dampness or carbonization. But until final failure is closely approached there is not a complete path from one pole to the other. There is rarely a direct short path at the point of maximum stress or elsewhere. If this is so: what causes the increase in watts loss and power factor in the bushing with the incipient defect?

A theory developed by the writer in 1930 to explain the observed results was, very briefly, this: The moist fissure between the compound and the porcelain acts as the plate of a condenser with the conductor the other plate. Therefore the bushing draws more current than a good bushing. But why has the power factor also increased? This is due to the resistance of the condenser plate itself, the moist fissure. The energy is not then lost *throughout* the bushing insulation but only in the fissure. The current flowing to the far part of the fissure must flow through the resistance of the near part of the fissure connecting it to a terminal.

The probability of the correctness of this theory was shortly confirmed by the presentation to the Institute of a paper on telephone insulators showing exact studies of a similar phenomenon. This paper by L. T. Wilson of the American Telephone and Telegraph Company is entitled: "A Study of Telephone Line Insulators," and can be found on page 1536 *et sec.* of the TRANSACTIONS for 1930. The paper should be studied by anyone interested in this subject. I shall not try to review it here but want to point out that the loss here considered is just one of seven discussed in this paper, and—this is most interesting—some of the other losses seem to have a close resemblance to losses that are occurring in oil-filled bushings and which cannot be accounted for by the theory set forth above. This telephone-insulator paper is also recommended to the cable specialists as similar theory may be helpful in explaining some things that are now rather obscure.

A most interesting thing about the theory set out above and the further results of the telephone insulator study is the indication that the power-factor method detects a failure or defect by observation of factors that are incidental to the development of the final fault rather than by measurement of the degree of final failure which may yet be almost infinitesimal. In cases where this is so, it is logical to conclude that the apparatus may be much more safely reconditioned without reinsulation than if the final fault had proceeded to measurable proportions.

Since no exact work, similar to that on the telephone insulators, has to my knowledge been done on the subjects of this paper, bushings and transformer windings, I shall not go to further length to expound this theory, but present it for those particularly interested to take up, test and present to us in complete and verified form.

G. B. Tebo (Hydro-Electric Power Commission of Ontario, Toronto, Ont., Canada): Mr. Gross has added materially to the already extensive records of power-factor tests on insulation, and has reached conclusions similar to those previously reported. The grand total of 60,000 tests appears to lend some weight to these conclusions but the absence of any data to show reduction in failures due to power-factor tests is rather disappointing.

There still appears a need for more critical discussion of the significance of power factor in rating the serviceability of an insulation. It can be shown that a bushing may be on the verge of failure without appreciable increase in energy loss or power factor; also that a substantial increase in power factor can be obtained without any increased hazard. In table III Mr. Gross recommends removal of any bushing having more than 0.5 watt loss at 10 kv. It is evident that a loss of 0.5 watt, per se, is not hazardous in a bushing weighing several hundred pounds. Some distinction should be made between energy losses uniformly distributed throughout a bushing, and those which cause serious disturbance in potential gradient and consequent overstress on the remaining good insulation.

The "hot collar" test referred to, was used by the writer in 1936, and as Mr. Gross points out, it is distinctly superior to the over-all power-factor test. Such faults as cracked and porous porcelains, entrapped water, etc., may be located by a "step-by-step" test but may not affect the over-all power factor appreciably.

The advantages claimed for the "hot collar" test are still restricted by the low test voltage (10 kv), the complex testing equipment and the necessity for interruptions on all equipment tested. Mr. Gross stresses the need for employing specialists in power-factor testing and interpretation of results. Such requirements may be related to the complexity of the testing technique.

The potential-gradient test (described in *Electrical World*, May 8, 1937) was developed to utilize the advantages of a step-by-step procedure and at the same time to provide a simplicity of equipment and technique comparable with that used in live-line insulator testing. During the past two years, the potential gradient test has been applied to about 2,500 bushings operating at 10 kv to 220 kv. Annual failures in this group have been reduced from an average of 15 in 1935 and 1936 to two in 1937 and none in 1938. Both bushings which failed in 1937 were abnormal when tested, but failed before removal.

Having thus practically eliminated failures of bushings by means of an annual live-line test, there appears little justification for tests to disclose defective lift rods, inferior oil, etc., which faults are detectable by the present visual inspection and oil testing schedules.

Considering the wide variations in power factor of the various material used for transformer-winding insulation, an attempt to rate the serviceability of the over-all insulation in terms of power factor seems rather arbitrary. It would be interesting to know how many of the 345 transformers showing power factors calling for "removal" were actually removed, and what faults subsequent inspection disclosed.

E. J. Rutan (Consolidated Edison Company of New York, Inc., New York, N. Y.): A study of the tables in this paper indicates that the limiting values of power factor selected for the different pieces of equipment can only be arrived at by the accumulation of considerable data. From several of the discussions which have already been presented, it would seem desirable to call attention to the fact that these tests have, in general, been made at less than rated voltage. The author's results do show when using the limits selected improvements in the condition of equipment classed as defective have resulted from overhauling. It does not follow, however, that the tests as at present conducted are giving the best clue to possible defects.

I think we can justify this statement from experience in dielectric tests of cable and other apparatus. In cable testing, the existence of ionization causes a very material difference in the power-factor readings obtained. In the Consolidated Edison Company over the past few years, we have been doing considerable work on certain pieces of high-voltage apparatus and insulators to detect what we have called, "the voltage of corona initiation." These measurements were started following an operating failure and to our surprise indicated that some equipment showed evidence of corona discharge at below normal operating voltages. Since then, this test has been included as part of the regular acceptance for certain types of insulation.

In view of the fact that in the power-factor measurement for the detection of possible faults we are looking for abnormal conditions, it is reasonable to expect that as faults develop there might be corona conditions at operating voltages. These same units, when new, might not show corona or ionization until several times normal voltage had been applied. It would seem, therefore, that measurements made at normal voltage would be more likely to disclose the development of undesirable faults. It might also be expected that the power-factor limits distinguishing good from defective equipment would be better defined.

In the past, the writer's organization has made a few power-factor measurements and efforts were always made to test at rated voltage. It is recognized, however, that there are difficulties encountered which at the present time have not been overcome. This, however, should not deter those who are regularly making these measurements from attempting to obtain data at rated voltage. Until this field has been explored, it is the writer's opinion that we will not fully realize the benefits of this type of measurement for diagnosing insulation troubles.

F. J. Vogel (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): Mr. Gross' paper furnishes data showing the results of several years' experience in field testing and is of great value both to operators and manufacturers. These results show shortcomings in materials used and in design practices. They also show the desirability of using checks to keep apparatus in good operating condition and avoid failures and expensive repairs and loss of service in the field.

There are several factors in power-factor testing of transformer insulation which I would like to mention. The company with which I am associated made power-factor tests for a period of a year or so in the factory on power transformers. The purpose of this was to accumulate data as to what power factors might be expected on new equipment. Due to the careful processing and drying out in the factory it might be expected that the results of the power-factor tests would be fairly uniform and to be, therefore, of little significance. This was actually found to be the case. For this reason the use of power-factor tests has been discontinued on transformers. It might also be pointed out that the power factor varied somewhat with different designs in such a way that the method is not suitable for factory testing.

It might be desirable to call attention to the fact that in service high power factors are not always caused by moisture. Oxidation and oil deterioration lead to high power factors in the oil even though dry. It is of interest that high power factor due to this cause does not result in any loss of dielectric strength. This has been demonstrated by tests on sample barriers ranging from very low power factors to 40 or 50 per cent power factors. Both 60-cycle and impulse tests showed no change with power factor.

It is of great interest that spare units not excited may deteriorate due to moisture. This might be expected particularly in transformers breathing to the outside atmosphere whether directly or in combination with an expansion tank. Where oil has been heated slightly above atmospheric temperature it has been found that it will keep fairly dry. Oil, however, which may become colder than the atmosphere and is in direct contact with the atmosphere can condense moisture and gradually become quite wet. Even transformers which breath in air through a calcium chloride breather may become quite wet due to the oxidation of the oil forming water which is not easily removed.

Mr. Gross has also called attention to the deterioration of cork gaskets. This material was the best material we knew of some years ago for use as gaskets. It is of interest that materials have recently been put into use which promise to deteriorate very little and which may last indefinitely.

F. C. Doble (Doble Engineering Company, Medford Hillside, Mass.): The paper by I. W. Gross summarizing authentic and instructive information from more than five years of consistent field testing of bushing and transformer insulation by the power-factor method is a credit to the author and should be of value to those in the industry who are responsible for the maintenance of high-voltage insulation.

It is significant that a 10-kv 60-cycle test has been adequate to maintain a completely reliable operating schedule on equipment rated from 13 kv to 132 kv.

Early in the development of field testing by the power-factor method, some insulation engineers felt that a 10-kv test voltage would be entirely inadequate for testing equipment rated by voltages higher than 10 kv. Also some others felt that an off frequency even up to 1,000 cycles would be desirable in order to get away from certain difficulties due to induction from parts of the 60-cycle system other than those under test and to mitigate possible loss effects due to the action of low frequencies on composite insulation.

The paper under discussion typifies a wide experience with dielective loss tests in the field correlated with failures of insulation of all voltages up to and including 220 kv that has proved conclusively that a 10-kv 60-cycle dielectric and power-factor test is adequate for a reliable economical maintenance program.

Referring to Mr. Montsinger's discussion, I agree with his statement that the greater complexity of construction and increased variety of designs of transformers as compared to bushings make it more difficult to interpret the results of power-factor tests into a reliable transformer-maintenance program. However, I believe that it is not too optimistic to expect that a reasonable degree of standardization of test values can be derived in view of the very simple tables that now cover the entire bushing range that was thought to be just as hopeless some years ago when field test by power factor first began.

Pertinent to Mr. Montsinger's request to the author for an explanation of the fact that spare transformers deteriorate at a much higher rate than those in service I believe that more attention should be given to the electrical characteristics of water in oil. Recent investigations indicate that it is possible for water to be present in oil in a low-loss form that is not revealed by ordinary electrical tests, such as dielectric breakdown or power factor, to a much greater degree than is shown by the literature that describe this phenomenon.

In this low-loss form the water is no apparent handicap to electrical operation. However, a drop in temperature may cause the water to change its electrical character so that it becomes high-loss water which may be a serious operating hazard. The spare transformers pass through a much wider temperature cycle than corresponding transformers in service with a resulting tendency to faster deterioration in a given time.

I. W. Gross: The numerous discussions given of this paper indicate the subject of field testing of insulation is a very live one at the present time.

The question of correcting power-factor readings to a standard temperature and the methods for so doing is one on which we have spent considerable thought and time. Mr. Cole has pointed out that he has taken this into account by using different power-factor limits on bushings, depending on the temperature of the oil in which the bushing is located. Another method on which we have been working is that of assigning a temperature to the bushing on the basis of the composite parts which are at different temperatures. For example, the bushing temperature may be rated on ambient air, copper temperature at the top of the bushing, or oil temperature of the apparatus in which the bushing is located; or in the case of oil-filled bushings it may be based on the temperature of the oil in the bushing. Undoubtedly, some further study in refinement is possible in arriving at the most desirable basis for temperature.

Mr. Wetherill has pointed out the theoretical justification for the test on fibrous insulation parallel to the fiber structure. It is quite fortunate from a practical point of view that this test along the fiber, such as along the surface of cylindrical insulating members, has proved to be an adequate test to detect the presence of moisture, as it would be decidedly burdensome and complicated to make routine tests radially. While it is true, as Mr. Wetherill points out, that the highest per cent of bushing failures (figure 6 of paper) occurs during the lightning season, it is also true that in the cases of bushing failures in the early part of the year when general weather conditions are cold, with subsequent thawing and rain, there is a rise in bushing failures which indicates to us the possibility that moisture, which had entered the bushing prior to failure, had become destructive by penetration into or through the insulating material. As pointed out in the paper deteriorated gaskets are contributory factors under severe weather conditions. Several years ago we experienced a number of bushing failures immediately following a protracted cold spell followed by thawing and rain in the early part of the year. These failures were not accompanied by lightning but appeared to be due to deterioration of the bushing by the entrance of moisture under severe weather conditions.

Mr. Montsinger and others comment that the type of transformer design may affect the interpretation of power-factor readings. This point is well taken and, as pointed out by him, undoubtedly a large number of tests on different types of transformers will be required before we can determine transformer faults with the same certainty that is now possible with bushings. However, the work which we have been carrying on during the past few years seems to indicate, with our present knowledge of the art, that there are many other factors in the detecting of transformer faults which at the moment far outweigh the difference in transformer design. This point, however, should be given further consideration.

In answer to Mr. Montsinger's question regarding the types of faults which have been found in transformers, so far as we have been able to determine, these faults have been due to the entrance of moisture into the transformer and have in most cases been successfully removed by drying the transformer by conventional, recommended methods. With practically few, if any, exceptions, we have not discovered other types of faults in such defective transformers at the time they were serviced as a result of the power-factor test.

In many cases, of course, the oil has deteriorated where it has been in service for some length of time, and on reservicing, it is always reconditioned or replaced. I do not recall that we have had any cases of seriously deteriorated insulation attributed to anything except absorbed moisture.

As brought out by many of the discussers, there is undoubtedly a great deal of research work to be done in studying the deterioration of insulation in a complicated, composite structure such as a transformer winding with its insulation of conductors, sections, cores, etc., and it is hoped that a well organized and carried on study of this problem will be made in the future.

The deviation of power factors, concerning which Mr. Montsinger asked, is very valuable in determining the condition of transformer insulation in the field, not only by comparison of insulation between transformers of the same design, manufacture, rating, etc., but also by comparison of insulation between primary and ground, secondary and ground, and interwinding insulation. We have sometimes detected faults by comparisons of this type.

Messrs. Chubbuck, Rutan, and Doble have all commented on the power-factor testing on higher voltages than 10 kv employed in our work. As pointed out by Mr. Doble, studies made so far indicate that 10 kv is adequate for the purpose. It is to be expected, however, that at higher test voltages approaching the operating voltage of the equipment, corona formation may be detected in some cases. This, however, with our present experience with practical field testing seems to be more a question of insulation design than one of equipment maintenance.

It should not be lost sight of, too, that to attempt to test field equipment which ranges all the way from 2,300 volts up to 230 kv would undoubtedly require considerably more elaborate test equipment as regards voltage supply than has generally been considered practical in the field. Unless there is some distinct advantage, which so far has not been apparent, to be gained by the use of high voltage in the order of 100 kv or so, we believe it is a better plan to retain a practical working limit of voltage until such time as research developments show that a higher voltage is essential to the satisfactory maintenance of equipment.

Mr. Goodwin's theory on the reason for failure of compound-filled bushings is quite interesting. A number of other theories have, of course, been set up, discussed and explored in the development of the present test set which we are now using.

Mr. Tebo touches on several points of interest as regards testing procedures, methods, equipment, and results obtained. In the first place, while the paper did not report numerically the reduction in failures of bushings or other equipment since power-factor testing work was started, there is abundant evidence to show that material reductions have taken place. This information, however, is not in the form of statistical, numerical data, but rather comprises the frequency of complaints from the field of equipment failures and also the verbal reports of the different properties on which testing work has been carried on. In fact, at the present time we are using three test sets in an attempt to carry out a yearly test schedule on oil circuit breakers, bushings, and transformers, and the results of testing have been so successful in improving the operating performance of equipment that we from time to time receive urgent requests from the field that the schedule be hastened to take care of testing their equipment on a more frequent basis to forestall trouble.

While, as pointed out by Mr. Tebo, it is theoretically possible to set up conditions of faults in bushings where a serious operating hazard can exist on a bushing without an appreciable increase in energy loss or power factor, still we should not lose sight of the fact that experience seems to show that actual occurrences of this kind are very infrequent. Likewise, the theoretical consideration of a $^{1}/_{2}$-watt loss at 10 kv in a bushing may exist without the bushing being a hazard on the system must be correlated with the practical experience obtained in testing bushings where losses of such magnitude are found and inherent faults in bushings have been detected. The possibility of these two conditions existing is, of course, admitted, but their probability seems remote.

Regarding the hot-collar test referred to in the paper, Mr. Tebo has apparently misunderstood our opinion of its place in test work and the importance of this type of test in detecting faults. It is not our opinion that this type of test is superior to the over-all power-factor test. It is merely a supplementary test which, when used in conjunction with the over-all power-factor test, has been useful in detecting some types of faults in particular types of bushings. This hot-collar test, so far as we know, was first described by Mr. O. E. Fawcett of the West Penn Power Company early in 1936 and was first used on our property subsequent to this.

Further, Mr. Tebo's implication that the testing technique which we are employing is complicated and therefore requires "specialists in power-factor testing and interpretation of results" is an opinion with which we quite emphatically differ. It often happens that a test device which requires merely the turning of a handle and the reading of an instrument scale falls far short of obtaining satisfactory results unless the results are understood and analyzed by competent and skilled men.

Considerable advantages result by having the tests promptly interpreted and remedial measures taken at the time of the tests. Mr. Tebo's statement that failures have been practically eliminated on some 2,500 bushings tested by the potential-gradient method warrants some comments. The absence of failures in 1938 (which is approximately only half of the current year) and the fact that the two which failed in 1937 were abnormal when tested leave the results very inconclusive. It should be borne in mind that to remove from service all bushings which are merely "abnormal" on test would place a heavy financial burden on the operating company which could not be tolerated. The degree of abnormity must be evaluated in terms of operating hazard. It is often true that an attempt to draw conclusions from incomplete data is often more harmful than beneficial.

We question the ability of any test method to eliminate all failures of bushings in service. If it should be possible to accomplish this, Mr. Tebo's statement that "there appears little justification for tests to disclose defective lift rods, inferior oil, etc.," is not in accord with operating experience in our company where we have found defective lift rods by the power-factor test and have eliminated them before breaker failure has occurred. The importance of field insulation testing lies in testing all major equipment, if possible, rather than to confine the tests to only a small part of it such as the bushings alone.

One type of fault the potential-gradient method applied to bushings cannot detect is faulty conditions of the insulation on the bushing within the apparatus, that is, below the bushing mounting flange. Faults of this type have been found by the power-factor method.

Mr. Vogel points out that a high power factor of the oil does not affect the insulation, and we presume he has in mind that if the fault should be localized in the oil (in a transformer), then servicing the oil would be a suitable means of reconditioning the transformer. This indeed is an interesting point, but it should be borne in mind that if the high power factor of the oil is due to contamination by moisture, then over a period of time that moisture may have worked into the insulation and become concentrated at some point in the insulation structure which is vital to the successful operation of the equipment.

In closing this discussion there is one broad point of view that we wish to emphasize, and that is, in field testing of insulation of the type described in the paper, we are dealing with a most complicated structure consisting of oil, paper, fibrous insulation, wood, etc. In many cases it is fortunate indeed that a power-factor test does give us an indication of the condition of the insulation as compared with the insulation of that equipment when initially new even though we do not know all the theoretical reasons why it does. Those who choose to take chances in operating a system with insulation known to be far different from what it was in its original condition must, of course, run the risk of equipment failure. Just how bad such insulation may become, and still result in satisfactory operation of the equipment is a point which is not known at the present time, but it is hoped that as our test work continues, it will be possible to obtain some valuable information on this point over a period of time.

A Self-Checking System of Supervisory Control

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MEMBER AIEE

Synopsis: This paper describes a new type of supervisory control system which was developed to reduce the selection time in large, multistation applications. The principles are based on the use of short and long electrical pulses and circuit designs not requiring a check-back code for assuring accuracy. It is equally applicable to a two-wire telephone line or a carrier-current channel. The design is quite flexible, permitting many alterations and additions to satisfy local conditions peculiar to its problems. The theory behind the elimination of the check or selection is explained.

Most modern systems of supervisory control are based on the logical principle of checking a selection before performing an operation. To do this, a checking code duplicating the selecting code is returned from the substation to the dispatching office. This insures that the desired unit has been correctly selected for operation.

The self-checking system, here described, obtains the same assurance of correct selection without the necessity of returning a duplicate of the selecting code. Thus, the over-all selecting time is reduced, particularly in the larger multistation systems. The usual initial operation of station selection is also eliminated since we can look at the whole system as a single station. Each remote piece of apparatus is assigned a definite code. The resulting saving of time is important, particularly when a carrier-current channel is used, since it minimizes the time during which outside interferences can tend to disturb or mutilate the signalling sequences.

In the design of the self-checking system, two types of selecting pulses are used. They differ from each other in their length or in the time of energizing the line. The short pulse has a characteristic time of the order of one-tenth

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of a second. The long pulse is purposely lengthened to approximately three times the time element of the short one.

Each selecting code is made up of the same number of total pulses and the same number of long pulses. By this means, the possibility of incorrect selections is eliminated. The explanation of this will be apparent from the circuit descriptions to be discussed later.

In the smaller applications, there is no advantage in the self-checking system. As the number of total pulses increase, the number of possible selection combinations enlarge enormously. This is apparent from figure 1. It is for this reason that the self-checking system is economical and most beneficial where there are many operations and several substations to be controlled and supervised.

From a given number of total pulses, the maximum number of selection combinations occur when the number of long and short pulses are equal. As an example, let us consider the case where eight pulses are used. The formula for determining the total selections may be written:

$$N = \frac{T \times (T-1) \times (T-2) \ldots (S+1)}{L \text{ (factorial } L)}$$

where

N = total number of selections
T = total number of long and short pulses
L = total number of long pulses
S = total number of short pulses

In this case, should three long pulses be used, the number of shorts would necessarily be five.

$$N = \frac{8 \times 7 \times 6}{1 \times 2 \times 3} = 56$$

However, should there be four long pulses, we have

$$N = \frac{8 \times 7 \times 6 \times 5}{1 \times 2 \times 3 \times 4} = 70$$

Should five long pulses be employed, we arrive at the same total as with three.

$$N = \frac{8 \times 7 \times 6 \times 5 \times 4}{1 \times 2 \times 3 \times 4 \times 5} = 56$$

If our system were composed of approximately 50 units, the scheme using three long pulses would be used since less total time is required.

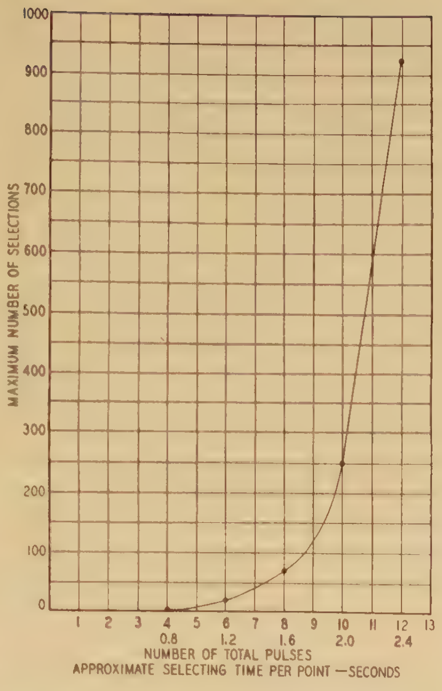

Figure 1. Curve showing the selection time in seconds for any unit out of a known maximum, given a code with a definite total number of impulses

Where ten total pulses are required, four long pulses permit selecting any one of 210 units. On the basis of 0.1 second for a short and 0.3 seconds for a long pulse, it is apparent from the foregoing that with an increase in selection time of 0.4 seconds, the size of the system may increase from 56 to 210 points. Due to the natural limitations of the number of contacts available on standard relays, less than the full theoretical number of selections is practical. The usable codes, even in the larger systems, are at least half of the theoretical total.

An even number of total pulses is advisable for purposes of balanced circuit design. Also, an even number of long pulses is preferable to an odd number. In the circuit design, the first half of the total pulses is called the group selection, while the second half is known as the point selecting pulses. For example, consider the case where a total of ten pulses is used. If the total number of system points is 100, the codes would be assigned so that there would be two long pulses in each of the first and second groups of five pulses. Using a system of numbering whereby the numbers represent the long pulses, code 14–79 would mean that the first, fourth, seventh, and ninth pulses were long while the remaining ones were short.

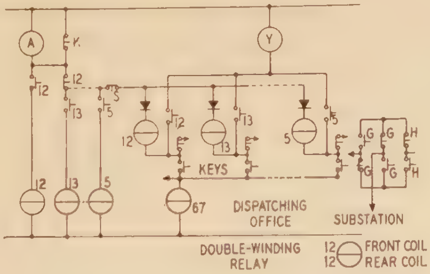

Figure 2. Code set-up circuit outlining method of establishing a definite code

The group codes would be 12–13–14–15–23–24–25–34–35–45.
The point codes would be 67–68–69–60–78–79–70–89–80–90 (the 0 denotes the tenth pulse).

This represents a ten by ten layout or 100 total points.

The codes would be:

12–67	13–67	14–67	15–67	23–67
12–68	13–68	14–68	15–68	23–68
12–69	13–69	14–69	15–69	23–69
12–60	13–60	14–60	15–60	23–60
12–78	13–78	14–78	15–78	23–78
12–79	13–79	14–79	15–79	23–79
12–70	13–70	14–70	15–70	23–70
12–89	13–89	14–89	15–89	23–89
12–80	13–80	14–80	15–80	23–80
12–90	13–90	14–90	15–90	23–90
24–67	25–67	34–67	35–67	45–67
24–68	25–68	34–68	35–68	45–68
24–69	25–69	34–69	35–69	45–69
24–60	25–60	34–60	35–60	45–60
24–78	25–78	34–78	35–78	45–78
24–79	25–79	34–79	35–79	45–79
24–70	25–70	34–70	35–70	45–70
24–89	25–89	34–89	35–89	45–89
24–80	25–80	34–80	35–80	45–80
24–90	25–90	34–90	35–90	45–90

From this, it is apparent that the selecting time of any one unit is the same as that for any other unit in the same system, since each code must contain the same number of long and short pulses.

The order of preference of reporting the codes in case of more than one attempt to start at the same instant is determined by the long pulses. The code with the first long pulse will take preference over one having a short pulse at that time. This is also true in multistation layouts where the station which is sending a short pulse locks out if some other station is sending a long pulse. All points have "storage" circuits so that there is no possibility of losing an indication under such circumstances.

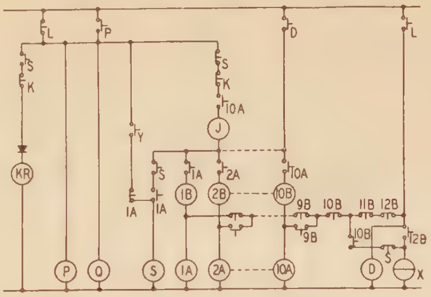

Figure 3. Simple short-pulse counting scheme used for recording the short pulses in a given code

The first application of this system was made on a pair of 287-kv power lines approximately 270 miles in length. The line circuit consists of a carrier-current channel of 60 kilocycles. Connections to the lines were so made that operation is possible even though either transmission line is open circuited or grounded.

In this case, ten total and four long pulses are used. However, the number of required operations demanded that the codes have up to three long pulses in either the group or point codes. When the group has one long pulse, the point must contain three, etc.

This application has many other features individual to the local conditions and these will be omitted in the general description to follow. There are two dispatching boards, one at Boulder Dam and the other at Los Angeles, on which all operations must report simultaneously. Should the Los Angeles board fail to receive a signal due to any cause, the dispatcher at Boulder is automatically notified. Again, interlocking is used so that the dispatcher cannot attempt a wrong operation. Thus, it is arranged so that a ground switch cannot be closed at one end of a line section if a line disconnecting switch is closed at the other end. Such are examples of special circuits which may elaborate on the fundamentals as will now be described.

Description of Scheme of Selection

Figure 2. As the dispatcher operates a point selection key (key 12–67, for instance) a circuit is completed through the operating coils of relays 12 and 67. As they close, locking circuits are formed by contacts on relay 12. They also open the circuit to other group and point relays. Figure 4 will show how their contacts make the first, second, sixth, and seventh pulses long. Relay *Y* is used to start the pulsing.

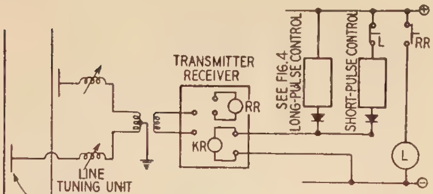

Figure 4. Impulse circuit used to impulse the carrier and method of coupling to high-voltage lines

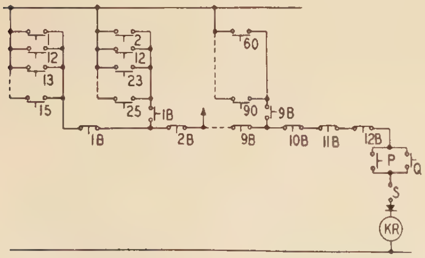

Figure 5. Long-pulse control scheme showing method of inserting the long pulses in their proper position in a given code

It will be seen that one set of point relays and only one may be operated at one time even though several point-selection keys are operated at the same time. This feature is not absolutely necessary at the office since the dispatcher would not operate more than one key at one time. It is required at the substation, however, since several breakers might open simultaneously. The office connection is made similar for the sake of uniformity.

To explain the action of the guard circuit, suppose the dispatcher operated keys corresponding to codes 12–67 and 13–67 simultaneously. Both relays 12 and 13 may operate momentarily but relay 12, being first in order, opens the positive feed to relay 13 so that only relay 12 can remain operated over its locking winding. The selection keys are thus wired in series sequence so that only the first one in the sequence is operated.

It will be noted here also that the numbers of the relays operated correspond to the numbers of the pulses which are made long. Should a code be operated which requires three long pulses in either the group or point sections (code 123–6 or 5–890, for example), the second windings of the necessary relays are connected in series by contacts of the point selection key which corresponds to that particular code.

Figure 3. When relay *Y* operates, a circuit is closed to relay *S* or sending relay. Being connected through a break contact of relay *L*, this circuit is effective only as long as relay *L* is de-energized, so that a pulse received from the substation at the same time that the circuit for *S* is closed will prevent the operation of relay *S*.

When relay *S* operates, it closes a circuit for the keying relay *KR*, which places carrier current on the high-voltage transmission lines. This results in the operation of all receiving relays (*RR*) (shown in figure 4). Neglecting for the moment the sequence of pulsing and the control of the long pulses, relay *L* is caused to pick up and drop out with the carrier-current pulses.

The pulses are counted by the counting relays 1*A* to 10*A* when relay *L* is energized and by relays 1*B* to 10*B* when relay *L* is de-energized. The first operation of relay *L* energizes relay *D* as well as 1*A*. Relay *D* is slow releasing when de-energized and does not drop out between pulses.

As long as relay *L* is operated, relay 1*B* is short-circuited and cannot operate even though the contact of 1*A* has completed its operating circuit.

When relay *L* releases after the first pulse, the shunt across relay 1*B* is opened and relay 1*B* picks up in series with the operating coil of 1*A*. As relay 1*B* operates, it transfers the *L* circuit to 2*A* so that it operates in response to the second pulse. Relay 2*B* operates as *L* drops out at the end of the second pulse. The remaining relays of the counting chain operate in the corresponding manner as the pulsing continues.

Figure 4. This shows the sequence of pulsing the carrier current. From figure 3, the keying relay *KR* was energized by the contact of the sending relay *S*. The contacts of the keying relay complete the transmitter oscillator and amplifying circuits thus applying carrier energy to the lines. All receiver relays pick up and, in turn, energize relay *L*. As relay *L* operates, it not only advances the counting chain of figure 3, but opens the keying relay circuit. As the keying relay drops out, carrier energy is removed from the transmission lines, resulting in the de-energization of all receiver relays. Thus, the counting chains in all stations step ahead simultaneously. The function of the long pulse control of the keying relay will be evident from figure 5. Even though the short pulse circuit is opened by relay *L*, a long pulse keeps the keying relay energized and carrier on the high-voltage carrier-current circuit.

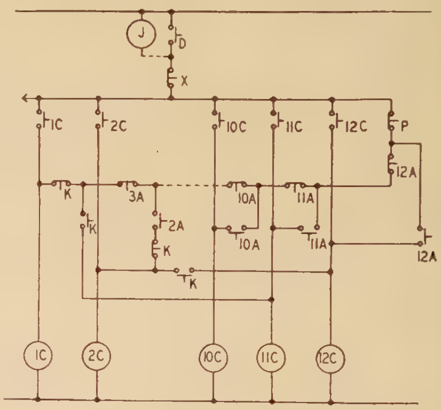

Figure 6. Long-pulse counting circuit used to record the position of the long pulses in a given code

Figure 5. For selection purposes, four of the pulses must be long. This is accomplished over long-pulse control circuit which also operates on the keying relay. To transmit code 12–67, pulses number 1, 2, 6, and 7 must be made long,

while the other pulses, that is, 3, 4, 5, 8, 9, and 10, must be short. As soon as relay S is energized, a circuit is completed by the make contact of relay 12 to the keying relay KR. Relays P and Q are normally energized through a break contact of L. These relays are slow to release and do not drop out immediately when relay L is energized. Carrier energy is thereby kept on the line and all relays RR and L remain energized. After a predetermined interval of time, relay P, whose circuit is opened by relay L, drops out and opens the circuit of slow-releasing relay Q. Relay Q also drops out after a certain time and opens the circuit of the keying relay KR, thus removing carrier from the line and dropping relays RR and L. Thus, each one of the four long pulses energizes the keying relay for a definite period of time.

Figure 6. As relay P drops on the first long pulse, it operates a long pulse register relay $1C$. This takes place at the sending station and all of remote stations. The duration of the long pulse is increased by the drop-out time of relay Q in order to give the remote stations sufficient time to operate the C register relays and to take care of unequal dropping times of the various P relays in the other stations. Other long pulses are under control of relay P in the same manner. Thus, during the third, fourth, and fifth pulses (of code 12–67) no circuit is completed for the KR relay in the long pulse control circuits, and relay P has no opportunity to drop. Register relays $3C$, $4C$, and $5C$, therefore, cannot operate. The same is true of $8C$, $9C$, and $10C$ of this particular code. At the end of the tenth pulse, all stations would have relays $1C$, $2C$, $6C$, and $7C$ operated and no others. As relay L picks up on the tenth pulse, relay $10A$ opens the circuit to relay KR, so that no further pulses can be transmitted. (See figure 3.) Relay D, receiving no further pulses from line relay L, releases after a short interval and opens the original holding circuit for the counting and code relays. Since ten pulses have been received, these relays are held up through the winding of relay J. Relay J closes through this circuit and operates the point selection relay B or F (B is at the office and F at the substations) corresponding to the selection registered on the code relays.

Figure 7. In the present case, code relays $1C$, $2C$, $6C$, and $7C$ are operated. The group selection circuit (controlled by the C relays operated during the first five pulses) is prepared after the eighth pulse by the operation of relay $8B$. Since $1C$ and $2C$ are energized, relay $12D$ is operated. Also, since $3C$, $4C$, and $5C$ are not energized, the operation of relay $12D$ picks up relay $G12$.

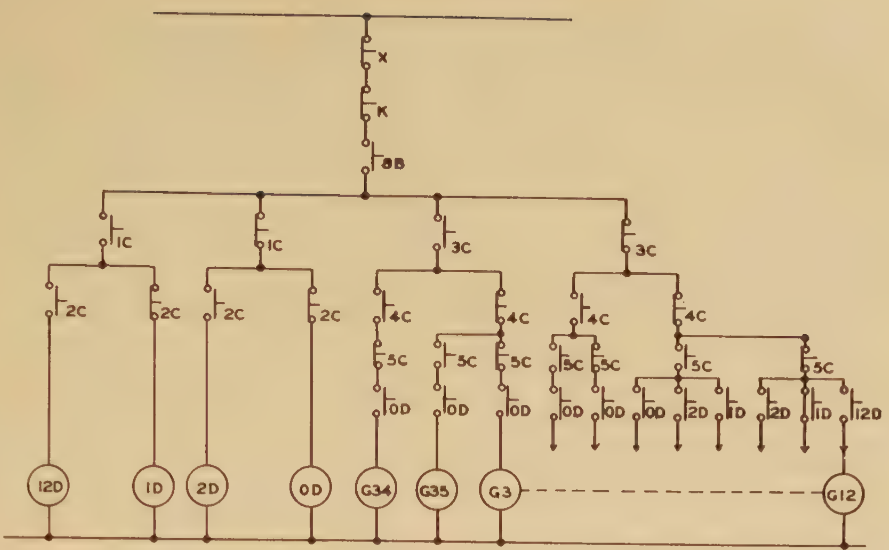

Figure 7. Group selection circuit employed to distinguish the group of a code

Figure 8. After the end of the tenth pulse and the operation of relay J, a circuit is prepared for the operation of the point selection circuits (controlled by the C relays operated during the last five pulses. Since $6C$ and $7C$ are energized, relay $67E$ picks up. The operation of relays J, $67E$, and $G12$ complete the circuit for $F12–67$ since $8C$, $9C$, and $10C$ are de-energized. As $F12–67$ operates, it extends its operating circuit to relay K, which also picks up and closes a locking circuit for itself and $F12–67$. Relay K opens the energizing circuit for the point selection relays so no more of them can operate and also drops the counting and code relays as well as relays J and S. They are thus restored to their normal position. Relay $10B$, as it operated at the end of the tenth pulse, opened the circuit of relays Y and 12, which in releasing drop relay 67. High resistance relay A (see figure 2) picks up and holds the selection until the key is restored to its normal position.

At this stage, the office has completed the selection of a point and is ready to receive a check code from the substation. At the substation, since no check is required on the selection, a check showing that something was received is desirable where a carrier-current channel is employed.

Circuit Design Eliminates Possibility of Wrong Selection

Before continuing with the operation of the equipment, the group and point selection circuit safeguards against a wrong selection will be amplified.

The circuit for relay J is completed only if relay $10A$ has been operated in response to ten pulses on the line. If less than ten pulses are sent, relay D will release after the pulsing ceases, but relay $10A$ will not be operated. No new holding circuit is established for the counting and long-pulse register relays, and they release immediately without attempting a selection.

If more than ten pulses are received, the eleventh pulse will operate the lock-out relay X, which locks up until the set is released. Relay X opens the locking circuit of the long-pulse register relays, causing them to drop out and also stop the transmitting of impulses. No selection can then be made until the equipment is released.

Relay J, which can only operate if ten pulses (no more and no less) are received, closed the point-selection circuits. A point-selection relay can be operated only if four long pulses have been received and properly registered on four of the register relays $1C$ and $10C$.

Inasmuch as the group code contains either one or two long pulses in the first five, either one or two of the C register relays $1C$ to $5C$ must be operated. If there is no long pulse in the first five, none of the relays $1C$ to $5C$ is picked up, and no group-selection relay ($G1$ to $G45$) can operate. Consequently, no point selection can be made. If only one long pulse is received in the first five pulses, one of the relays $1C$ to $5C$ will be closed. As relay $8B$ operates, one of the group selection relays $G1$ to $G5$ will close. Should two long pulses be received in the first five, two of the $1C$ to $5C$ relays will be energized, resulting in closing one of the group-selection relays $G12$ to $G45$.

If three or more long pulses are received in the first five, an examination of the contact circuits will prove that no group-selection relay can operate, thus preventing any subsequent point selection.

In other words, a group-selection relay can be operated only if either one or two long pulses are received in the first five.

When the group codes contain one long pulse, the point codes must contain three. Likewise, two long pulses in the group code demand two in the point codes. Thus, the point codes contain either two or three long pulses, depending on the preceding group code.

Examination of the contact circuits of the point-code relays 6*C* to 10*C* will show that no point selection circuit can be completed when no long pulse is received in the last five pulses. The same is true when only one long pulse is among the last five.

When two long pulses in the last five are received, ten point-selection circuits are prepared which lead only to those group-selection relays associated with two long-pulse group codes. Therefore, a point selection can be made only if two long-pulse group-selection and two long pulse point-selection pulses are properly received.

If three long pulses are received in the last five, ten other point-selection circuits are prepared, leading only to those group-selection relays which are associated with the one long-pulse group codes. Therefore, a point-selection relay can be operated in this case only if one long-pulse group and three long-pulse point-selection pulses are properly received.

Should four or more long pulses be in the last five, the contacts of relays 5*C* to 10*C* cannot close a point-selection relay circuit.

Summing up, it is clear that a point-selection relay can be operated only if:

(*a*) Relay *J* is operated in response to at least and not more than ten total pulses.

(*b*) One group-code and three point-code relays are operated.

or

(*c*) Two group-code and two point-code relays are operated.

(*d*) At least and not more than four long pulses are received.

All other combination of pulses will not complete a selection.

Substation Check

While no check is necessary on the accuracy of the selection at the substation, the use of carrier current as a channel makes it advisable to get some sort of a signal back to show that the carrier equipment is working. To do this, two pulses are returned which, at the same time, indicates the present position of the breaker or device to be operated. If, at that time, the device is closed, a long and short pulse code is sent to the office. If the device is in the open position, a short and long pulse code is transmitted.

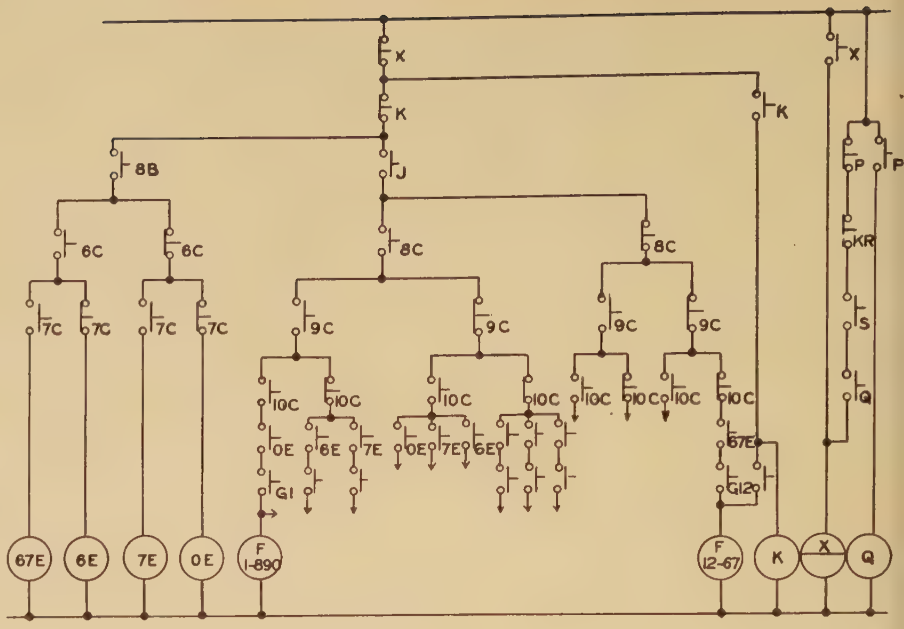

Figure 8. Point selection means used to isolate the point individual to a code

The substation sending follows the same sequence as has been described at the office except that the keying relay is opened at the end of the second pulse. The counting and code relays are restored to normal. At the office the two pulses are received registering on 11*C* or 12*C* depending on whether the selected device is closed or open. A circuit is completed only if either the first or second pulse is long. If both are short or if both are long, the contacts of 11*C* and 12*C* keep the circuit open. The relay energized in response to this signal controls the red and green lamp relay. Should the selected device be closed, the first pulse is long (and not the second) and relay 11*C* is operated. The lamp relay is energized connecting the red lamp in the circuit. Relay 12*C*, which picks up when the first pulse is short and the second one long, causes the lamp relay to drop out, changing the lamp indication from red to green.

Operation Control

At the same time, connections are made to prepare the circuits for the transmission of the operation control codes. The point-selection lamp at the office is lighted only after the reception of a correct indication code from the substation. If, at this time, the selected device should automatically change its position, the new indication code is immediately transmitted to the office.

The dispatcher may now operate the master control key which sends through a three-pulse code, depending on the position of the twist key of the selected point. The codes used are a long-short-short combination for closing and a short-short-long combination for tripping. The relays thus operated have their locking circuit through the twist key providing an antipumping feature.

After the three pulses are transmitted, further transmission is stopped by relay 3*A*. At the substation, the circuit is set up only if three pulses are received and the first or third one long. The device then operates and the changing of its auxiliary switch sets up the sending circuit to initiate transmission of the new indication code. As the new code is received at the office, the lamp relay is controlled as previously described.

In order to insure that the lamp relay has properly changed, a check code is sent from the office to the substation. A single long pulse is sent if the lamp relay is energized while a single short pulse denotes the de-energized position of the lamp relays. When one of these types of pulses is received at the substation, relay 11*C* is operated if the red lamp is lit, but will not be under the green lamp condition. In either case, if the check code from the office agrees with the position of the selected device, no further action takes place. If they do not agree, a new indication code is transmitted.

The dispatcher may keep the selected point as long as desired and repeat the closing and tripping operations at will. Meanwhile, the device is constantly supervised, and any new position is automatically indicated at the office.

Releasing the Selected Point

When the dispatcher desires to release the selected point, he restores the point-selection key. If no pulses are being received at this time, restoring the point selecting key opens relay *A*. Relay *A* is arranged to send a single release pulse.

In order to make a last check of the lamps at the office against the actual position of the selected device, the release pulse is made long if the red lamp is lit and a short pulse for the green lamp. This action is the same as previously described except all equipment resets to normal if the signals agree.

All other stations which have locked out are also automatically unlocked by the reset pulse.

Automatic Operation From the Substation

When a device changes its position in the substation, the selecting code is sent to the office in the same way as during a selection with the exception of the check code. Here, both sets of signals originate at the substation, so the indication code of two pulses follows immediately after the ten-pulse selecting code as pulses eleven and twelve.

An audible alarm and flashing disagreement lamp informs the dispatcher of the change. The disagreement lamp is so named because the position of the control key and indicating lamps are not in agreement. Its chief function is to assist the operator quickly to locate the unit which has operated automatically in the remote station.

Should several devices change position simultaneously, they report to the dispatcher in sequence. The order of preference is settled by the code since a station locks out if it is receiving a long pulse while sending a short one. Also, within a station, the code with the first long pulse, where another code has a short one, will be sent through first.

Conclusion

The new self-checking system is particularly applicable to large multistation applications, especially where carrier current is used as the controlling channel.

The possible source of code mutilation may be summed up:

(*a*) One or more pulses are lost due to relay failures or line trouble. In this case, a selection cannot be made.

(*b*) One or more pulses are added due to relay failures or line trouble. Again, no selection can be made.

(*c*) Two or more short pulses may flow together to form a long pulse. This results in less than the correct number of pulses and also too many long pulses. Therefore, no selection results.

(*d*) A long pulse may be split into two short pulses. The selection cannot be completed because of too many pulses as well as an insufficient number of long pulses.

(*e*) Should the long-pulse indicating relay *P* fail to release on a long pulse, no selection results as too few long pulses are received.

(*f*) Also, if relay *P* should drop out on a short pulse, too many long pulses are received and no selection is possible.

Thus all reasonable possibilities of wrong selections are reliably prevented and no check-back is necessary.

Discussion

F. Von Voigtlander (Commonwealth and Southern Corporation, Jackson, Mich.): Increasing interest is being shown by operating companies in the application of supervisory control schemes to power systems, chiefly as a means of reducing operating costs and improving service.

In contemplating the application of supervisory control to a given power system the first consideration would be whether or not the control system was applicable. I would, therefore, like to ask the author what is the field of application of this control system?

If it was found that the installation of supervisory control could be justified on the given power system, the next question would be what does this system offer that is not available in other modern control systems?

An important consideration in the successful operation of automatic equipment is maintenance. Equipment may suffer not only from lack of maintenance, but from overzealous maintenance as well. Another question I would, therefore, like to ask is what form and extent of maintenance is required by this control system and is there any way in which the equipment would give warning of faulty maintenance before actual failure took place.

D. R. Pattison (nonmember; Pennsylvania Electric Company, Johnstown): We are large users of supervisory control equipment and have found this type of equipment very reliable provided it is not overmaintained. We are extremely interested in the general trend toward simplification and have always wondered why supervisory control systems outgrew the original audible type, which in our estimation is the simplest form of remote control.

It has been our belief that the operating companies should at all times keep their remote-control requirements along logical and practical lines and avoid frilly requirements which of necessity complicate the equipment.

The manufacturers have been very generous in this respect and have at all times attempted to meet the special requirements which in a large number of cases represent whims of individual engineers or operators.

It is felt that the self-checking system offers a simplification in that the back and forth checking operation is eliminated.

E. E. George (Tennessee Electric Power Company, Chattanooga): Operating experience with remote control of various kinds indicates that the author's proposal to eliminate the check back system is a step in the right direction.

To those who feel that the multiplicity of relays in extensive applications of supervisory control may involve operating delays due to testing and maintenance, is suggested that the methods of the communication companies be imitated. In dial switching systems a large group of relays are mounted on a base plate which has plug and jack connections so that the whole base with these relays can be instantly removed from the switchboard and replaced by a spare unit. The connector and selector switches used in the step-by-step dial system are good examples of this construction.

G. De Croce (nonmember; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Replying to Mr. Von Voigtlander, this system differs from other systems in that it is applicable to large multistation applications because in these instances the selection time remains a constant and the over-all equipment is materially reduced.

The best known method of anticipating trouble is to make visual inspections of the equipment. This inspection enables the maintainer to determine the cleanliness of the equipment and permits an observation as to the regularity of operation of the operating relays.

Mr. Pattison raises a point which should be generally digested by the industry at large, that is, the elimination of overspecial features and requirements. If this thought is carried out it will generally make for a reduction in cost and a simpler equipment.

Present-day supervisory control equipments have outgrown the audible type because it is generally accepted that a continuous indication of the position of remotely disposed devices is far better than to have an operator dial for a supervision and depend entirely upon his hearing to determine the exact position of the device.

Mr. George's contribution to this paper indicates the confidence in this type of equipment by those operating companies who have had previous experience with supervisory control.

The reliability of this type of equipment and its freedom from maintenance service has been demonstrated by the number of successful installations now in operation. It is felt that in view of present field experience the need for a removable jack-type relay where the relays are grouped becomes unnecessary.

Transmission Features of the New Telephone Sets

By A. H. INGLIS
ASSOCIATE AIEE

Synopsis: The new telephone instruments now being introduced by the Bell System result in an outstanding improvement in transmission performance in service. The evidence for this, as obtained by comprehensive laboratory and field tests, is presented here, together with a discussion of the factors responsible for this superior performance and of the consideration involved in its appraisal.

NEW TELEPHONE instruments are being applied in the plant of the Bell System to the desk stand, wall set, and handset, and result in markedly improved transmission performance. The new instruments are associated with the antisidetone feature which is also applied to the older sets already in plant. The selection of these particular designs from the wide choice made possible by new design technique, materials, and manufacturing methods, has been based on developments in the methods for quantitatively rating the relative merits of different designs. In general, there has been consistent effort over a period of years, to base these ratings primarily on performance in service rather than on laboratory tests.

The factors influencing service performance are so many, and so complicated in their relationship, and are in so many cases difficult or even impossible for the designer to evaluate or control, that their net effect on performance cannot be predicted with certainty by laboratory methods. Of necessity, such methods involve a limited selection of primary test conditions, and an even more limited selection from the possible combination of these conditions. This is particularly true in the rating of the transmission performance of a telephone set. Laboratory tests are essential in the study and analysis of design problems, and are invaluable similarly in interpolating, supplementing, and explaining service performance results. In determining the reaction on the user of the transmission features of possible designs, however, the field performance test has been found of first importance in deciding what particular characteristics to include in the new telephone instruments and circuits.

Important Transmission Characteristics of the New Telephone Sets

The specific transmission design features of the new instruments, are described elsewhere.[1] The purpose here, therefore, is to discuss primarily the outstanding improvements in performance resulting from the application of the new instruments and the antisidetone feature which has been available for some time.

These improvements are

1. Those due to the station circuit, which, as compared with the previous station circuit,

   a. Largely reduce the efficiency of the sidetone path between transmitter and receiver, without materially affecting the electrical efficiency of the set in transmitting or receiving. This means that sounds, either noise or speech, which are picked up by the transmitter, are reproduced in the receiver of the same set at a much lower level.

   b. Reduce the susceptiveness for certain types of party line sets to interference with reception by noise set up by power transmission systems.

2. Those due to the physical characteristics of the transmitter and receiver.

Several of these features have been available for some time, and have, of course, been introduced into the plant as they became available. The new transmitter and the antisidetone circuit, for example, have been standard for some years and have already been installed in large numbers.

Figure 1 shows both the new handset and the desk-stand forms of mounting, including all these features as integral parts of their design. The new desk-type transmitter and receiver can, of course, be used with wall sets.

The schematic drawing of figure 2 indicates the general arrangement of parts in the new station transmission circuit for either type of set.

In describing the results produced by these transmission features, and the methods employed in measuring and rating these results, it seems desirable to include some discussion of the characteristics of a telephone conversation as distinguished from a direct, face-to-face conversation, so that the various effects of the new circuits and instruments may be seen in as correct relative proportion and as generally comprehensible form as possible.

Some Elements of the Station Transmission Problem

In either a telephone or direct conversation, successful communication depends on the characteristics of the talker and of the listener, and their reactions to each other and to the character of their surroundings. In a direct conversation such, for example, as across a desk, the environment is in general the same for both talker and listener, and their ears are materially aided by their eyes. In a telephone conversation, however, not only may the surroundings of talker and listener be entirely different, but a third element, the telephone system, is added to the environment of each user, which complicates his reaction, not only to his own surroundings, but also to the other party to the conversation. Furthermore, for obvious economic reasons, the natural binaural reception of direct conversation, with its advantages in discriminating between sounds from different directions, is replaced in the telephone conversation by a monaural medium.

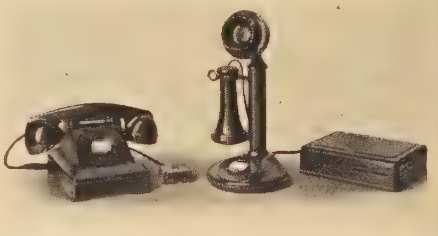

Figure 1. The new handset and desk-stand telephone instruments

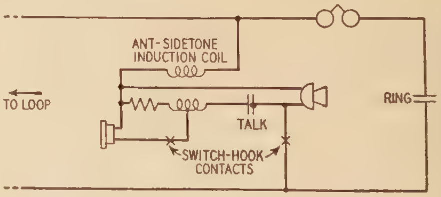

Figure 2. Schematic transmission circuit of antisidetone coil

Fundamental differences of this kind between telephone and direct conversation must be taken into account in the design of a telephone transmission system

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[1] For all numbered references, see list at end of paper.

if satisfactory results are to be obtained. For example, the talker is accustomed in a direct conversation to regulate his talking volume by what he himself hears under prevailing noise conditions (which incidentally are the same for the listener), by the ease with which he hears the other party, and by the ease with which the listener appears to hear him. By experience, under ordinary conditions, the first factor mentioned, the loudness with which the talker hears himself, probably comes to be the primary control on his talking volume.

These various factors also serve to regulate talking volumes in conversation by telephone, but their magnitudes and the relations between them differ from the condition of face-to-face air-path conversation and vary from one type of telephone connection to another. For example, the "sidetone" of the telephone set, being materially higher than the air-path sidetone, deceives the talker, not only by making him think he is talking louder than he really is, but also by apparently modifying the noise conditions under which he is talking in the pickup and amplification of room noise by his telephone transmitter. Since, in addition, the efficiency of the telephone circuit itself may be different in the two directions of transmission, the loudness heard by one party may differ more from that heard by the other than in the case of air transmission. Then, too, noise conditions may be and frequently are quite different at the two ends of the telephone circuit. Figure 3*A* shows the probability of noise of various average intensities at subscribers stations as determined by several surveys covering a large number of locations. On the assumption that any one of the stations represented by these data may with equal probability call any other one, figure 3*B* has been computed, showing the probability of noise at the two stations of a telephone connection differing by more than a certain amount. It will be noted that there is about an even chance of the noise at the two ends differing by more than 12 decibels. In view of these differences, a person's judgment of how well he is heard and understood cannot be as direct as in the case of air transmission.

In addition, the transmission over the commercial telephone system affects the quality of the received speech more than the usual room surroundings in air-path transmission. While acoustic resonance and reverberation in a room do distort speech, in the extreme case to a point where understanding may be difficult, such a condition is distinctly unusual. Equal freedom from distortion in a telephone system is a more difficult and expensive condition to obtain than in direct conversation a few feet from a listener. Something less than perfect reproduction must suffice, for the present anyway, if costs are not to be prohibitive.

All of these differences involve the acquiring by the user of a set of telephone habits which differ from those he has acquired in direct conversation. The problem of the transmission design of a practical telephone system requires, then, for a satisfactory solution, not only a determination of the proper speech levels to be delivered, and of the sidetone characteristics which will, under the conditions of a telephone conversation, give optimum results with the noise encountered, but also a decision as to what particular frequency range and characteristic to choose. Properly designed, a telephone transmission system should minimize, to the degree consistent with costs, its inherent differences from direct conversation, and make it easy for the ordinary user to get, without undue effort, results which are satisfactory to him in comparison with direct conversation.

In the earlier days of telephony, the problem presented appeared much simpler. It was, in effect, unidimensional, calling primarily for more efficient instruments and circuits; more and more power delivered to the listener's ear. While methods for the control of sidetone were not unknown, the importance of such control was not fully appreciated. Little choice was available in the quality of reproduction provided by transmitter and receiver, because of meager design knowledge.

Relatively recent, and quite rapid developments in knowledge of the problems involved, in materials, methods, and measuring facilities, have now presented the necessity for a solution in essentially a three-dimensional form. These three dimensions may be described as volume, noise, and quality. The solution of the problem on this basis is obviously more difficult, and has required the development of methods for quantitatively evaluating and rating their characteristics in terms of some common yardstick.

Methods of Rating Transmission

For reasons already suggested, such a yardstick must be based on service performance—on the results obtained by actual users in the course of day-to-day telephone service.

Extensive investigation has indicated that the best comparative measure of this transmission performance in local exchange service is to be found in the time rate of the occurrence of repetitions required by subscribers for understanding telephone conversations.[2] Or, more explicitly, when two transmission conditions have the same repetition rates, all other service factors being equal, these conditions are taken to be equal with respect to transmission performance. Where two conditions are not alike it is usually possible to evaluate the difference in the repetition rates for the same users by inserting distortionless loss in the better condition until both have equal repetition rates.

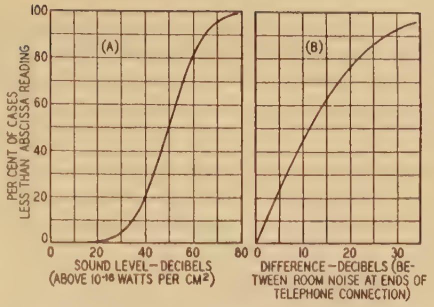

Figure 3. Noise conditions at telephone stations

Thus, by taking as a reference, a typical telephone circuit of specified make-up, the effects of various factors such as distortion, noise, attenuation, sidetone, or type of instrument, may all be expressed in the common terms of the reference circuit trunk which will give the same repetition rate.

Instead of making this adjustment in every case for the purpose of evaluating the relative performance of different test conditions for the same users, the evaluation may be made rather closely over a limited range by the following typical relation derived from repetition observations on circuits containing trunks, the losses of which were varied over a range of values.

$db = 50 \log_{10} R_1/R_2$ (see reference 3)

where R_1 and R_2 are the repetition rates of two conditions under comparison, and the *db* figure is the change in the reference trunk which has the same relative effect on the repetition rate.

Such a method is, of course, somewhat cumbersome, and requires a large amount of data to iron out random variations and individual peculiarities of little general interest. But as the fundamental rating method, supplemented by laboratory test, it has been systematically used in studying the value of the antisidetone circuit and in selecting instrument characteristics.

Supplementing the repetition observations, it has been found useful in service rating to obtain data on speech levels delivered to the line for each condition observed. This has been done with the volume indicator, a vacuum-tube voltmeter so designed that the reading is approximately proportional to mean syllabic voltage.[4] The information thus obtained is useful not only in analyzing the results of service tests but in determining typical values for speech levels, necessary for laboratory tests.

Laboratory tests are of two general types, objective measurements and subjective tests. Transmission measurements cover a wide field with objectives ranging from the physical analysis and study of different designs, to the determination of over-all performance characteristics of structures and systems. It is these latter tests that we are more particularly interested in here, as most descriptive of the physical properties of importance in providing telephone transmission service.

Subjective tests in the laboratory may be said to be midway between physical measurements and field performance tests. Made under controlled and somewhat artificial conditions, they indicate quantitatively the capabilities of a telephone system in transmitting articulate speech under the particular conditions of the test. They cannot, of course, indicate the relative probability of occurrence, and hence importance, of these different conditions, nor predetermine how well the subscriber will avail himself of the capabilities provided.

Consideration of some of the results of investigations in both laboratory and field will do much to explain the rather large transmission improvement realized by the introduction of the new sets in actual service, particularly if examined with the conditions of a direct conversation as a basis of comparison.

The Station Circuit

There are two characteristics of the new station circuit of particular importance from a transmission standpoint.

Reduction of Sidetone

The first is the antisidetone induction coil through which the transmitter and receiver are coupled to the line. This coil comprises, in addition to three transformer windings, a balancing network. The circuit, made up of the four elements, transmitter, receiver, line, and network, coupled by the transformer, functions in such a manner that the transmitter and receiver are in conjugate relationship, that is, voltages produced by the transmitter are balanced out and do not affect the receiver. Theoretically, such a circuit, with pure resistance elements, can be perfectly balanced at all frequencies with complete elimination of sidetone, and at the same time be as efficient as can any transformer coupling in an invariable telephone set,[5] for the transfer of power from the transmitter to the line, and from the line to the receiver.

This type of circuit is not new in principle, and many varieties are known and have been described.[6] Many of these arrangements, for one reason or another, are not suitable for application. Some, for example, call for impedances of transmitters or receivers differing widely from those available. Certain others are not economical for common battery service, where the transmitter must receive its battery supply from the line. Still others require relatively complicated and expensive cording and switchhook arrangements. The circuit which has been chosen for general common battery subscriber station application, and shown schematically in figure 2, is not only as simple and as easily adapted to Bell System conditions as any, but permits a coil design which is economical to manufacture as well as efficient in performance. Other types of antisidetone circuit have been adopted for local battery station service and for operators' telephone sets.

The theory of operation of this antisidetone circuit has already been discussed elsewhere.[7] It is intended here to show the general purpose of the application, some of the considerations involved in the design, and the kind of results accomplished.

While in theory, complete elimination of sidetone is possible, as well as ideal efficiency of transformation, in practice, neither objective can be entirely realized. The unavoidably wide variations in line impedance looking from the set, ranging from high positive to high negative phase angle, and from a few hundred to more than a thousand ohms in magnitude, together with other practical departures from ideal conditions, necessitate a choice between a high degree of sidetone balance, and the standardization of a minimum number of coil designs. The variations in loop length and resistance, by their effect on transmitter battery supply, and consequently on transmitter resistance, furthermore cause variations in the absolute transmitting and sidetone efficiency of the terminal set, which must be taken into account in the station circuit design.

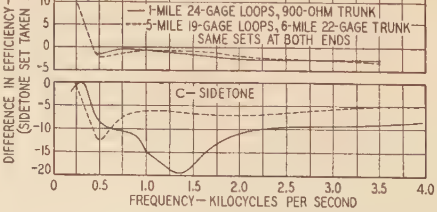

Figure 4. Circuit efficiency of antisidetone circuit versus sidetone circuit

The actual design chosen is so arranged as to favor sidetone balance on average and shorter loop conditions where transmitter battery supply is greater, with consequent higher sidetone, and to favor transmitting and receiving efficiency on longer loops where battery supply is low. Since loop losses are greater for transmitting than for receiving because of transmitter battery supply loss, the ratio of the transformer is such as to favor the transmitting efficiency of the set somewhat in comparison to the receiving efficiency. This has the advantage of raising the transmitted speech level further above line noise. The same idea, of course, was followed in the design of the sidetone set.

The resultant antisidetone circuit adopted and here discussed, as compared with the sidetone circuit previously in general use, when equipped with the same transmitter and receiver and on the same loop and trunk, reduces sidetone on the average by about ten decibels. Under the most unfavorable conditions of use, the reduction is unlikely to be less than about seven decibels compared with the corresponding sidetone connection. Under the best conditions of balance encountered the reduction may be as much as 12 decibels. On the effective basis of transmission the average net improvement in transmission which results is about six decibels.

From the electrical circuit standpoint alone, the efficiency of the antisidetone arrangement is below that of the sidetone set in the order of about one or two decibels in transmitting and in receiving, which is necessitated by the limitations of practical design and circuit conditions discussed above.

Figures 4*a* and 4*b* show for transmitting and receiving, respectively, the difference in efficiency, with respect to frequency, of the antisidetone set from the sidetone set, each with the same instruments. Two subscriber loop and trunk conditions are shown, an average loop and trunk, and a long cable connection.

Figure 4*c* shows the variation in sidetone reduction with frequency, of the new set as compared with the corresponding standard sidetone set, for the same two circuit conditions as above. The curves are indicative of the effect of variation of circuit impedance on sidetone balance, in changing not only the magnitude, but the frequency range in which the best balance occurs.

Data of this sort alone do not, of course, indicate the relative transmission performance of the two sets. The beneficial effect on the telephone user of the large reduction in sidetone must be evaluated on the same yardstick as the losses in transmitting and receiving efficiencies which, in the practical case, accompany this reduction in sidetone. McKown and Emling have shown the effect of changes of this sort on the results obtained by the ordinary telephone user, in terms of net effective transmitting and receiving loss, as determined by service observations.[8] Their data, shown in figure 5, are relative to the sidetone of a reference set. The heavy solid lines are the original experimental data, the dotted extensions to these curves being extrapolated.

In addition to the original ordinates, others are shown which are of interest. They are based on the results of loudness balance tests, and while not perhaps of great precision, do approximately indicate the relationship of the sidetone of a telephone conversation to that for direct speech, and illustrate the differences in the effects of sidetone for transmitting and for receiving.

On each curve are indicated the average sidetone value of the standard sidetone and the new antisidetone set, each, as before, with the new transmitter and receiver. There is also shown the range of sidetone for each type of set, within which practically all service conditions will fall. This indicated range takes into account not only variations in sidetone balance due to line impedance variations, but changes (with loop resistance) in battery supply to the transmitter. It should be noted that in only a few cases is the absolute sidetone of the antisidetone set on the worst sidetone conditions, as high as or higher than that of the sidetone set on the best sidetone conditions, and then only by a small amount. Furthermore, in spite of the wider variations in sidetone of the antisidetone set, these variations are over a range such that the resultant variations in effective losses are smaller than for the sidetone set.

Considering figure 5*a*, it will be noted that for either sidetone or antisidetone sets, the sidetone is louder than for natural speech sidetone, which, as noted before, makes the user think he is talking louder than he actually is. The average sidetone reduction of ten decibels for the antisidetone set results in less of this restraint on his talking level, with a resultant net effective gain in transmitting of about four decibels compared with the sidetone set.

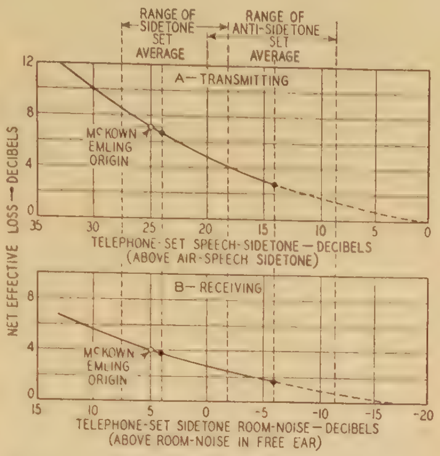

Figure 5. Effects of sidetone on user of telephone

In receiving, figure 5*b* sidetone introduces an effective loss by the reproduction in the telephone ear of room noise picked up by the transmitter. It will be noted that for the antisidetone set, the reproduced noise is in general appreciably lower than the room noise itself. Inasmuch as room noise also interferes directly with received speech in the telephone ear by leakage under the receiver cap, the contribution to the total noise of the sidetone pickup of the antisidetone set is in most cases small. This is not true for the sidetone set, where in many cases the sidetone noise may constitute the principal interfering noise. The resultant net effective gain in receiving is about two decibels compared with the sidetone set.

This is a good illustration of the type of information which can be obtained only from a field study. For example, the relationships indicated on figure 5 are dependent on how far away from the mouthpiece of the transmitter and at what level the speaker talks, and on how tightly to his ear he holds the receiver. These in turn are resultants of all the conditions of the particular telephone conversation. If incoming levels are so high as to be uncomfortable, the receiver may well be held farther away from the ear. In that event, of course, the sidetone conditions of the set become relatively less controlling. The weight, size, and shape of the instrument in his hands may similarly affect the subscriber's use of it, the results he gets, and the relative importance of various factors of telephone design.

For such reasons, not only must laboratory performance tests be supplementary and subsidiary to field tests, but additional field tests must be the basis for determining the effect of any major changes in design, whether or not those changes are electrical, acoustical, or purely mechanical.

Considerations of this sort emphasize the importance of having clearly and explicitly in mind the conditions and relationships of direct conversation, as a general reference for the interpretation and explanation of the effects of telephone design on telephone conversations. The sidetone ordinates of figure 5, for example, not only suggest the difference in function of the antisidetone circuit in transmitting and receiving, but also emphasize the fact that the over-all sidetone resulting from the combination of circuit, instruments, and method of use, is the important factor rather than the sidetone circuit efficiency only. Such matters are easily lost sight of, if design is not properly co-ordinated in its correct perspective.

The reduction of sidetone provided by the antisidetone sets is of further advantage in two rather different ways.

In attaching a transmitter (which is an amplifier) and a receiver, to a common handle which mechanically couples the two, a condition is set up in which the gain under certain conditions may exceed the loss in the path made up of handle, air, and electrical sidetone circuit. Sustained oscillation, or howling, will then result between transmitter and receiver. Even if this point is not reached, but is approached within six decibels or so, impairment of quality results from incipient oscillation. The greater sidetone circuit loss of the antisidetone circuit provides an additional margin of safety against any such condition.

The granular carbon of the transmitter, and the design of the transmitter itself must be carefully controlled, or serious noise—transmitter "burning"—will cause noise in the receiver of the set. The mechanical and electrical wear and tear of service tends to make this transmitter noise worse. In the new transmitters this "burning" has been kept at a low inherent value throughout life. The antisidetone circuit, however, provides a margin of safety against the small amount remaining, so that with this set there is

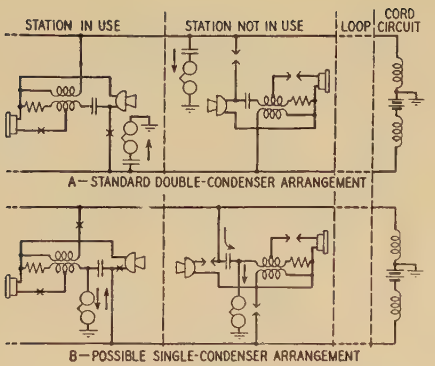
STATION IN USE
STATION NOT IN USE
LOOP
CORD CIRCUIT
A—STANDARD DOUBLE-CONDENSER ARRANGEMENT
B—POSSIBLE SINGLE-CONDENSER ARRANGEMENT

Figure 6. Ringing arrangements for party-line service

less likelihood of transmitter noise causing impairment of reception.

Reduced Susceptiveness to Interference

It will be noted from the schematic circuit drawing figure 2 that two condensers are used in the new sets, one in the antisidetone transmission circuit, and a separate one with the ringer. In some types of party-line practice, the ringer of the set is connected for some parties from one side of the line, and for the others from the other side to ground.

Figure 6 shows schematically two such ringing arrangements during the conditions of conversation, 6*a* as used in the new sets, and 6*b* with one condenser common to transmission and ringing circuits. It will be noted that in the standard circuit adopted (figure 6*a*), if any longitudinal noise voltages exist between the central office and station grounds, there is an equal voltage drop from each side of the line to ground through the ringing paths (assuming the two ringer condenser paths to be identical). The voltage drop across the terminals of the talking set is therefore zero and no noise results.

If the arrangement of figure 6*b*, corresponding closely to previous designs, were used, however, this condition would not obtain. The condenser of the station in use being common to the transmission circuit as well as the ringing circuit, the noise voltage drop across this condenser is introduced in the transmission circuit. In addition there are other paths to ground from each side of the line through the transmission circuit which are not of equal impedance. The net result is a residual noise current through the receiver of the talking circuit.

In the actual case, the impedance of all ringers and condensers is not identical and there are often more parties connected to one side of the line than the other. Even under these relatively unfavorable conditions, however, the two-condenser arrangement adopted reduces the susceptiveness of the set to interfering noise by as much as 15 decibels. A further material reduction is realized by the high impedance of the ringer used in the new sets, so that in most cases interfering noise at grounded ringer stations will not differ materially from that at individual stations where the ringer is bridged across the line.

It is interesting to note that this improvement is realized at little additional cost, since the transmission condenser, which must be of relatively high capacitance, is permanently bridged by the transmitter, so that it is protected from exposure to any large voltages, and may be of cheaper construction and smaller in size than would otherwise be the case. The ringing condenser on the other hand, while it must be constructed to withstand higher voltages, may be of relatively small capacitance, which gives more uniform and better ringing and dialing performance.

Characteristics of Transmitter and Receiver

Since the individual design characteristics of the new transmitter and receiver are discussed elsewhere,[1] attention here will be centered on the over-all effects of these characteristics in the complete transmission system, as indicated both by laboratory and by field test. As stated before, the problem may be more or less arbitrarily separated into three correlated problems—volume, quality, and noise.

As in the case of sidetone, these problems appear, perhaps, more nearly in a proper perspective, if considered in comparison with the corresponding factors in a direct conversation. It must be remembered that telephone service does not consist in the provision of a mechanism, per se, but in the provision of facilities for conversation, to which the mechanism should be incidental, however important. Since the inherent conditions of such a conversation are quite different in many respects from those of a direct conversation with which, consciously or unconsciously, it will be compared in its overall results, the parallelism in detail should not be too exact. Departures from the conditions of direct conversation in certain respects which are relatively unavoidable, may be best compensated for by deliberate departure in certain other respects. For example, the physical absence of one party to the telephone conversation, and the monaural nature of such a conversation, may be partially compensated for by delivering to the ear of the listener a somewhat higher speech level than he is accustomed to in direct conversation. The limitation of frequency band width imposed on the telephone medium, largely for economic reasons, may be minimized in its effects if the transmission characteristics in the available band are other than a facsimile of the corresponding band in direct conversation. All such measures must be employed with knowledge of their effect on the ultimate objective, that the telephone conversation may be easy and natural.

General Requirements

It is easily seen that for any particular over-all frequency characteristic of a telephone transmission system, there are practically an infinite number of ways in which it can be split up between transmitting and receiving characteristics. From this standpoint alone, then, there is no particular "best" transmitter or receiver frequency response. From other standpoints, however, certain general types of individual characteristics, both in frequency and efficiency, are to be preferred to others, particularly when considered in their practical application to an already existing telephone system. It has been pointed out[9] that, in general, development has been toward a telephone system where both transmitter and receiver are relatively uniform in their frequency characteristics. Induced noise appears to be so evenly distributed with frequency that such response would not appear to magnify the interference problem.

Transmitting efficiency should be as high as required to keep the speech well above induced noise but not so high as to cause excessive crosstalk into other telephone circuits. The maximum desirable received level is determined for a given telephone system by the limitations of the human ear in accepting with comfort speech levels above a certain intensity. Finally, the practical necessity of working as satisfactorily as possible in conjunction with the telephone transmitters, receivers, and sets in the existing plant during the period of transition, places a practical limitation on the amount of change that is desirable in relative levels of either transmitting or receiving.

With regard to frequency range, previous work[10] indicated the desirability of designing circuits to transmit frequencies from 200 or 300 cycles up to about 3,000 cycles. Gains in articulation and naturalness are realized by increases in this band width, but are progressively smaller for successive equal increments in frequency. A 3,000-cycle band properly used gives good transmission both in articulation and naturalness, but frequency limitation is essentially an economic one, subject to change as conditions change. Recent work on the new multiple-channel carrier systems has indicated justification in these systems for providing a somewhat wider band, from about 150 to about 3,500 cycles.[11]

Over-all Frequency Response

In describing the frequency characteristic of a transmission system it has become customary to refer to it as more or less "flat," where "flat" is assumed to be synonymous with "perfect" as far as the relative transmission of various frequencies is concerned. In measurements of the elements of an electrical circuit, from which this terminology came, the word is useful since, when the measurements are properly made, at any rate, the basis of comparison implied by the word "flat" is generally understood. This is also true, although probably to a more limited extent than is generally realized, when the term is applied to electroacoustic transmission systems, where free progressive, plane air waves of various frequencies are transferred to an electrical system, or vice versa, by means of microphones or loud speakers.

In the case of a telephone system, however, where a transmitter is placed close to the lips, and a receiver directly to one ear, and where the air waves are not free progressive, or plane, use of the word "flat" implies a basis of comparison which is not self-evident. Much effort has been given recently to establishing an appropriate reference system, sufficiently simple in concept and ease of specification, to be useful in this connection. The result of this work has been a reference telephone system which, when spoken into, would give the listener in all respects essentially the identical sensation he receives in one ear when facing the speaker directly, with an air path one meter long between the speaker's mouth and the listener's ear, in surroundings without reverberation or noise. Such a reference transmission system has tentatively been called an "orthotelephonic" system.

The point of interest here is that when measured by any suitable objective method, the frequency characteristic of this "orthotelephonic" telephone reference system is not "flat" by a considerable amount in the ordinarily accepted usage of the term. This departure from "flatness" is caused by such factors as the frequency directive characteristic of the mouth, cavity resonance of the ear, and disturbance of the sound field by the head. The individual contribution of some of these factors is not as yet definitely determined.

Furthermore, for reasons mentioned, it is not self-evident that a practical telephone system of limited frequency range, should be "flat" with respect to the corresponding frequency band in this more or less basic orthotelephonic system which is not limited in frequency range. Having decided on the band width that is desirable and justifiable, it must still be determined, therefore, what particular frequency characteristics are preferable in this band.

In selecting from the many possible choices, the particular frequency response that seems best, several factors must be taken into account. This has been done by a study (under the conditions of actual service) of the relative results of several different experimental instrument designs, varying in frequency characteristics. The over-all frequency characteristics of the resultant choice are indicated for two typical circuit conditions in figure 7. These measurements were made with the artificial mouth and ear[12] and are plotted with reference to corresponding measurements on an orthotelephonic reference telephone system. For comparison, the results of similar tests of the earlier Bell System handset[13] are shown also.

In considering these over-all telephone-system frequency-response characteristics in the light of previous discussion, there are several points of interest:

1. The large increase in response at both higher and lower frequencies with respect to the older handset, which in itself was a notable advance in this respect over previous types. This increase amounts to ten decibels or more from about 200 to 500 cycles and from about 1,700 to 3,000 cycles. This wider frequency range gives better naturalness of reproduction.

2. The type of the response. The general uniformity and absence of any marked resonance or irregularity is obvious. For either average or long loops the entire band from about 300 to over 3,000 cycles lies within a range of 15 decibels. It will be noted, however, that, for the average condition, the response at the higher frequencies (1,500–3,000 cycles) is distinctly above that for the frequencies below 1,500 cycles. This characteristic aids materially in the understanding of the low-intensity consonant sounds. The response on the longer loops would undoubtedly be correspondingly better if the high frequencies were raised so that the over-all characteristic more nearly resembled that for the average condition shown. It should be remembered, however, that for a standard set, to be used on all loop conditions, a response designed solely for the long loop, with its large loss at high frequencies, would be distinctly "tinny" and disagreeable in quality on average or short loops.

3. The materially smaller losses in the transmitted band for the average telephone connection than for the orthotelephonic system. Even for the long loop conditions the losses are no greater than for this orthotelephonic system up to about 2,200 cycles. In other words, for a large majority of telephone calls the received speech level will be higher for the same talking level than in the case of direct conversation at one meter distance. The desirability of this in a monaural system of limited frequency range has already been indicated.

Combined Effects of Circuit and Instruments

The part played by the antisidetone circuit in permitting better utilization by the subscriber of the capabilities of the telephone system, in increasing the level of received speech, and minimizing the effect of noise is summarized by the illustrative power level diagrams in figure 8, using typical values of room and line noise and other conditions.

The data shown were obtained by objective measurements with the artificial mouth, sound level meter, volume indicator, and artificial ear. Frequency weightings appropriate to the levels involved were employed in the sound level measurements.

Figure 8*a* shows, for the antisidetone set, the losses between the talker and listener under average room noise and circuit conditions. Figure 8*b* gives corresponding information for the sidetone set. For comparison, an approximate level diagram is shown also for direct speech. The relative speech levels at the transmitter for the two telephone conditions were adjusted to give volume indicator readings on the line in accordance with the results of service observations. The upper curves in each drawing

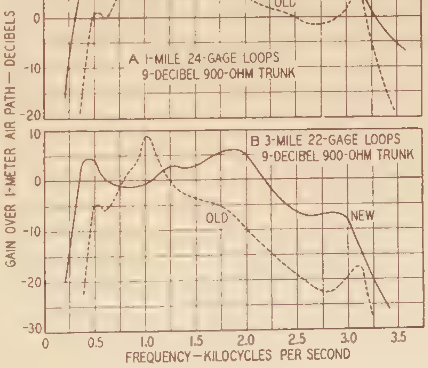

Figure 7. Over-all orthotelephonic frequency response of typical telephone connections

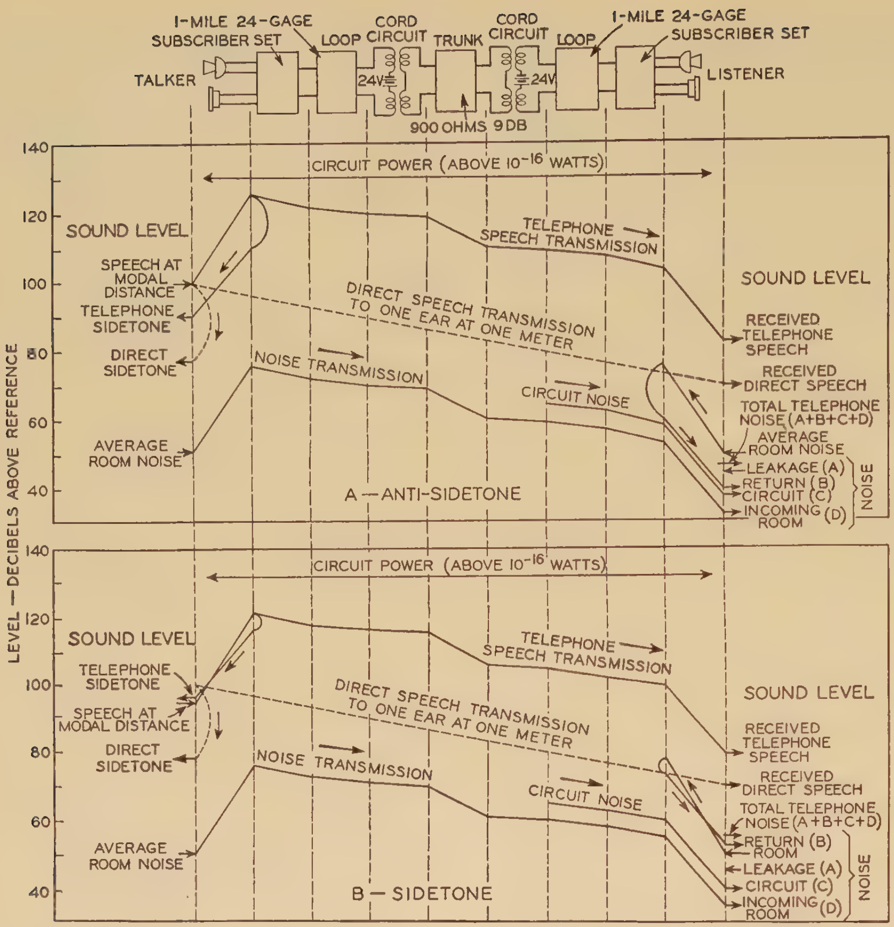

Figure 8. Power-level diagrams of typical telephone connections

are for speech and the lower for noise picked up by the transmitters.

At the transmitting end, the lower sidetone of the antisidetone set results in higher talking levels, with about four decibels higher speech level at the input to the circuit. In the over-all circuit, this gain is increased by the receiving end effect of the antisidetone circuit in minimizing the effect of room noise.

The total noise in the telephone ear, as shown on the drawing, has as its principal contributing factors,

1. Leakage of noise under the receiver cap.
2. Noise picked up by the transmitter and returned via the sidetone path and receiver to the listener's ear—termed "return noise."
3. Circuit noise.
4. Room noise picked up at the far end and transmitted over the circuit.

The different relative contribution of the "return noise" for the two sets is of interest. The net result is a total noise in the telephone ear, lower than the actual room noise for the antisidetone set, and higher for the sidetone set.

For the circuit and room noise conditions shown, the ratio between received speech level and noise is about 25 decibels for the sidetone condition, and 35 decibels for the antisidetone. The corresponding ratio for air transmission to one ear under the conditions shown is the order of 20 decibels.

Results of Laboratory and Field Performance Tests

It has been seen that the new sets are superior in volume and in minimizing the disturbances of noise. The frequency measurements just discussed have indicated marked superiority also in the quality of reproduction.

One measure of the effect of this reduced distortion is by means of the articulation test. Such tests have shown that for a typical telephone system equipped with the new telephone sets, 95 per cent of the letter sounds spoken into the transmitter are correctly understood by the listener. With air transmission, 98 or 99 per cent of letter sounds are correctly understood. The difference is almost entirely due to the broader frequency band transmitted by the air path.

With the final designs of the new sets, tests have been made by the methods developed for determining "effective" transmission.[2] The results of these tests have shown that the new sets under the conditions of actual service provide a marked advance in transmission performance. The average total transmitting and receiving gain is about 15 decibels on the effective basis of transmission, as compared to sets of the sidetone type used with the older type of instruments.[13]

Conclusion

In general, it appears that the notable transmission improvement which has been achieved in the design of the new telephone sets, in their freedom from distortion, higher effective volume, lower sidetone, and general convenience in use, makes possible a closer approach to the ease of a direct conversation than has hitherto been possible commercially.

Undoubtedly, further improvements in station transmission performance will, as in the past, be forthcoming with advances in the technique of design and manufacture, and in further knowledge of the requirements of the problem.

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Transactions

Papers and Discussions Comprising Pages 613–62 of the 1938 Volume

Noise Co-ordination of Rural Power and Telephone Systems

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THE co-ordination of telephone and power systems has been studied for about 15 years under the auspices of the Joint Subcommittee on Development and Research of the Edison Electric Institute and the Bell Telephone System. Until 1935 the noise frequency studies on distribution systems related chiefly to the types of systems employed in urban and suburban areas.[1] Between 1935 and 1937, the work was extended to include rural power and telephone systems, which differ in several respects from the systems employed in urban areas. Measurements of power circuit influence and telephone circuit noise were made on a number of representative rural systems in Nebraska, Iowa, Michigan, Ohio, Indiana, and Virginia, with the co-operation of the operating companies. These tests were supplemented by a theoretical analysis of the problem.

The investigation of the joint subcommittee indicates that it is generally practicable to secure satisfactory co-ordination of power and telephone facilities in rural areas from the noise standpoint with the types of power and telephone systems ordinarily employed when the inductive influence of the power circuits and the inductive susceptiveness of the telephone circuits are properly controlled. Such control of influence and susceptiveness includes the following:

1. Maintenance of relatively good voltage wave shape on the power system (i.e., harmonics arising in generators, transformers, and loads confined to relatively small magnitudes).
2. Suitable distribution of the loads and lengths of single-phase branches among the phases of three-phase power circuits.
3. Use of metallic telephone circuits with series and shunt unbalances to ground maintained within reasonable limits.
4. Suitable transposition of the telephone wires with respect to the power line.
5. Use of the higher impedance type of ringers where grounded ringers are required for party line service.

In particular cases, special co-ordinative measures may need to be employed in order to secure satisfactory conditions. The purpose of this paper is to discuss the factors affecting the inductive influence of rural power circuits and the inductive susceptiveness of rural telephone circuits. A summary is included of the more promising co-ordinative measures at present available for use in particular situations where such may be required. No attempt is made to present the large body of experimental and theoretical material which has been collected during this study, since this is available in other publications.[2]

The types of power distribution circuits usually encountered in rural areas are illustrated in figure 1, with the types of three-phase main lines and single-phase extensions indicated separately. A distinction is made between single-phase extensions directly connected to three-phase systems and those supplied through a step-down or step-up transformer. The latter arrangement is frequently used to provide an extension of different type or voltage from an existing system. In the systems tested during this study, these single-phase supply transformers ranged in capacity from 15 to 100 kva. In some cases, three-phase rural distribution systems serve also as lower voltage transmission systems supplying power to small towns in which a lower primary voltage is used.

The power distribution circuits in urban or suburban areas are generally relatively short and operate at high load densities. In rural areas, however, the distribution circuits tend to be longer and to operate at lighter load densities. On rural lines, therefore, harmonic charging currents and propagation effects, which are usually negligible in urban areas, may become of primary importance. The connected capacity of single-phase load transformers on the circuits tested ranged between 2 and 20 kva per mile of circuit. The lengths of the three-phase circuits tested ranged up to 65 miles, and individual single-phase extensions as long as 30 miles were encountered.

The inductive influence of a power system from a noise standpoint is determined by the magnitudes of the balanced and residual harmonic voltages and currents existing at various points. That portion of the harmonic residual current which returns in a path remote from the line conductors is often termed the "ground-return" current. The telephone influence factor (*T.I.F.*) of a power system current or voltage[3,4] in an inductive exposure is used as an index of the influence of that particular current or voltage on the noise-frequency induction in the exposed telephone circuits. It is the usual practice to express the influence of a current in terms of the product of its magnitude in amperes times its *T.I.F.*, this product being abbreviated as $I{\cdot}T$. Similarly the influence of a voltage is expressed as the product of its magnitude in kilovolts times its *T.I.F.*, this quantity being abbreviated as $Kv{\cdot}T$. These terms are used in this paper to express the influence of the balanced and ground-return currents, and balanced and residual voltages of rural power circuits.

Co-ordinated tests in exposure sections at roadway separations have shown that ground-return harmonic currents and harmonic residual voltages are generally the controlling factors in the influence of rural distribution circuits, rather than the corresponding balanced components. In exposures to the main power line, or whenever several miles of line extend beyond the exposure, the wave shape and magnitude of the *ground-return current* ($I{\cdot}T$) is usually the controlling factor in the over-all influence. For exposures near the end of a main line, or at any

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[1] For all numbered references, see list at end of paper.

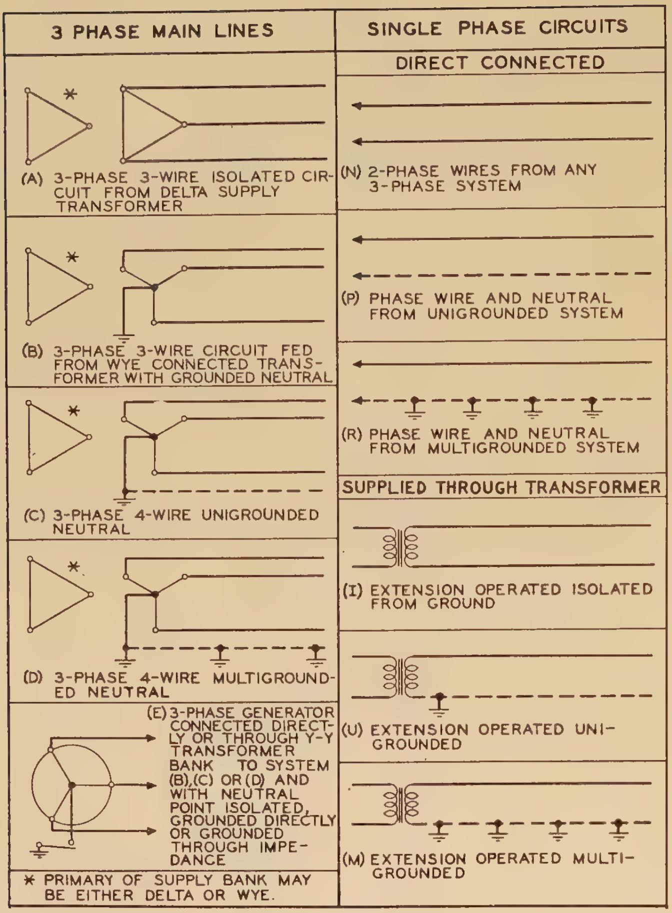

3 PHASE MAIN LINES
SINGLE PHASE CIRCUITS
DIRECT CONNECTED
(A) 3-PHASE 3-WIRE ISOLATED CIRCUIT FROM DELTA SUPPLY TRANSFORMER
(N) 2-PHASE WIRES FROM ANY 3-PHASE SYSTEM
(B) 3-PHASE 3-WIRE CIRCUIT FED FROM WYE CONNECTED TRANSFORMER WITH GROUNDED NEUTRAL
(P) PHASE WIRE AND NEUTRAL FROM UNIGROUNDED SYSTEM
(C) 3-PHASE 4-WIRE UNIGROUNDED NEUTRAL
(R) PHASE WIRE AND NEUTRAL FROM MULTIGROUNDED SYSTEM
SUPPLIED THROUGH TRANSFORMER
(D) 3-PHASE 4-WIRE MULTIGROUNDED NEUTRAL
(I) EXTENSION OPERATED ISOLATED FROM GROUND
(E) 3-PHASE GENERATOR CONNECTED DIRECTLY OR THROUGH Y-Y TRANSFORMER BANK TO SYSTEM (B),(C) OR (D) AND WITH NEUTRAL POINT ISOLATED, GROUNDED DIRECTLY OR GROUNDED THROUGH IMPEDANCE
(U) EXTENSION OPERATED UNIGROUNDED
(M) EXTENSION OPERATED MULTIGROUNDED
* PRIMARY OF SUPPLY BANK MAY BE EITHER DELTA OR WYE.

Figure 1. Types of rural power distribution systems

point along a short single-phase extension, the wave shape and magnitude of the *residual voltage* (*Kv·T*) is usually the most important factor. Therefore, these residual components are of chief interest in any discussion of the influence of rural power circuits.

Residual Harmonic Voltages

Residual voltages appear on three-phase power systems operated isolated from ground (figure 1*A*) as a result of the action of the balanced voltages on the unbalanced impedances-to-ground of the phase conductors. These impedances depend chiefly upon the length of circuit connected to each phase. Consequently, the residual voltages on a three-phase isolated system tend to be least when equal lengths of extensions are connected to each phase. Practically no residual voltage exists on a single-phase circuit supplied through a single-phase transformer and operated isolated from ground (figure 1*I*).

On three-phase systems operated with grounded neutral, residual harmonic voltages may either (1) be impressed directly upon the system, as in the case of triple harmonic voltages arising in direct-connected generators or a wye-wye transformer bank without tertiary delta, or (2) arise as a result of the action of balanced voltages upon unequal impedances-to-ground of the line conductors or connected loads. On single-phase extensions consisting of a phase wire and multigrounded neutral, the residual voltage is substantially equal to the phase-to-neutral voltage, since the neutral is at ground potential. The same is true of a unigrounded extension at the point where the neutral is grounded. However at points remote from the grounding point, the harmonic voltage from the neutral wire to ground may be comparable with the harmonic voltage from the phase wire to ground. The vector sum of the two voltages-to-ground (residual voltage) may therefore be considerably different from the voltage between the phase and neutral wires.

The range of residual *Kv·T* measured on various types of rural power circuits, in relation to the corresponding phase-to-ground *Kv·T*, is indicated in table I.

Ground-Return Harmonic Currents

The components which may contribute to the ground-return current (*I·T*) in a rural power line may be conveniently classified as:

(*a*) Harmonic charging currents.

(*b*) Harmonic components of the load current.

(*c*) Harmonic exciting current components arising in transformers and harmonics originating in connected loads.

The equivalent circuits of figure 2 illustrate the behavior of these three components on different types of single-phase lines. In the case of circuits 2*A* and 2*B*, the ground-return *I·T* is practically all

Table I. Summary of Influence of Rural Power Circuit Voltages

Type of Power Circuit	Number Cases Tested	Voltage T.I.F.			Phase-to-Ground Kv·T			Ratio Res. Kv·T / Ph-Gnd Kv·T		
		Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Three phase—11-13 kv										
Three-wire delta	1	13			87			0.14		
Four-wire-uni—from Δ-Y banks	7	17	7	36	124	55	250	1.1	0.16	2.1
Four-wire-uni—from direct connected generator	8	13	6	24	95	50	170	1.7	1.3	2.2
Four-wire-multi—from Δ-Y banks	12	21	8	62	151	60	450	0.9	0.4	1.8
Four-wire-multi—from direct connected generator	9	14	9	19	106	70	150	1.8	0.92	2.13
Single phase directly connected to three phase										
11 kv Delta	2	20	15	24	127	95	159	0.71	0.47	0.95
7.6 kv Delta	1	12			50			0.74		
Uni	4	17	14	22	128	110	165	1.03	1.0	1.08
Multi	4	17	11	27	129	85	210	1.0	1.0	1.0
2.3 kv Delta	3	26	8	40	36	11	55	0.49	0.40	0.62
Uni	3	19	16	23	46	39	56	1.0	1.0	1.0
Multi	4	21	19	23	49	46	56	1.0	1.0	1.0
Single phase supplied through transformer										
6.9–7.2 kv Isolated	1	17			56			0.006		
Uni	8	39	16	92	276	105	660	1.0	1.0	1.0
Multi	11	34	12	104	246	83	750	1.0	1.0	1.0
4.8 kv Isolated	2	37	35	38	88	85	90	0.034	0.034	0.036
Uni	3	40	13	57	191	64	280	1.02	0.95	1.06
Multi	8	53	11	172	258	50	830	1.0	1.0	1.0
2.4 kv Isolated	2	40	35	45	46	40	52	0.017	0.015	0.02
Uni	2	37	30	44	90	72	108	0.97	1.0	0.93
Multi	3	40	13	55	93	30	130	1.0	1.0	1.0

due to charging current, the load and exciting currents being confined to the line wires. The charging current is a function of the residual voltage impressed on the circuit and the impedance-to-ground, which in turn is dependent on the extent of the system. The impedance-to-ground of these systems is not affected by loads, although the voltage wave shape of the system may be modified by the presence of load, or harmonics generated in loads.

In the case of the multigrounded circuit (figure 2*C*), the ground-return $I{\cdot}T$ is contributed to by harmonic components of (1) ground-return charging currents, (2) load currents, and (3) transformer exciting currents.

The magnitude of the ground-return charging current component at any frequency depends upon the voltage impressed on the ground-return circuit and on the impedance-to-ground[2] of the circuit, neglecting loads, as seen from the point where the voltage is impressed. Sample curves of the calculated impedance-to-ground of a single-phase line are given in figure 3, showing the effect of frequency and circuit length. The maximum current results when the circuit length is such that series resonance (quarter wave length) occurs at the particular frequency in question. The higher the frequency, the shorter will be the circuit length for which resonance occurs.

Comparing the curves of figure 3 for the multigrounded and unigrounded condition, it appears that the impedance-to-ground of the *shorter* multigrounded circuits (i.e., less than quarter wave length) is higher than that of the comparable unigrounded circuit at any given frequency. This is one reason for the decrease in the ground-return charging current which often results when a circuit is converted from unigrounded to multigrounded operation. An additional effect results from the reactive component of the load current, which combines with the charging current at such an angle that further reduction in the ground-return current may result in the multigrounded case. In cases where the conversion results in changes in the residual voltage, or where the system is extensive (between quarter and half wave length), the change from uni- to multigrounded operation may either decrease or increase the ground-return charging current at a particular frequency.

Table II. Average Ground-Return I·T and 180, 300, and 420-Cycle Currents in Single-Phase Multigrounded Circuits Due to Transformer Exciting Current

Primary Voltage	Primary Ground-Return* I·T and Mils in Ground Per Kilovolt-ampere of Connected Single-Phase Transformer			
	I·T	Mils, 180 Cycles	Mils, 300 Cycles	Mils, 420 Cycles
2,400	0.6	5.0	1.3	0.3
4,800	0.3	2.5	0.6	0.15
6,900–7,600	0.2	1.7	0.4	0.10

* These ground-return values are taken as 60 per cent of the phase values.

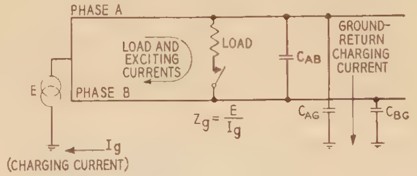
Table III. Summary of Influence of Rural Power Circuit Currents

Type of Power Circuit	Number Cases Tested	Voltage T.I.F.			Phase I·T Product			Ratio Gnd. Ret. I·T / Phase I·T		
		Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
Three phase—11-13 kv										
Three-wire delta	4	13			220	100	320	0.55	0.16	0.80
Four-wire-uni—from Δ-Y banks	7	17	7	36	400	40	790	0.42	0.16	0.92
Four-wire-uni—from direct connected generator	9	13	6	24	430	60	650	0.79	0.34	1.17
Four-wire-multi — from Δ-Y banks	12	21	8	62	515	40	1730	0.36	0.10	0.81
Four-wire-multi — from direct connected generators	9	14	9	19	470	60	820	0.6	0.51	0.83
Single phase directly connected to three phase										
7.2-7.6 kv Delta	1	12			110			0.41		
Uni	4	17	14	22	170	45	250	0.82	0.78	0.86
Multi	4	17	11	27	170	40	250	0.62	0.58	0.64
2.3 kv Delta	3	26	8	40	175	38	400	0.09	0.07	0.11
Uni	3	19	16	23	72	7	140	0.44	0.39	0.50
Multi	4	21	19	23	90	7	175	0.51	0.43	0.62
Single phase supplied through transformer										
6.9-7.2 kv Isolated	1	17			160			0+		
Uni	9	39	16	92	106	23	350	0.75	0.28	0.94
Multi	12	34	12	104	143	30	535	0.61	0.50	0.65
4.8 kv Isolated	2	37	35	38	170	50	290	0+	0+	0+
Uni	3	40	13	57	215	80	430	0.82	0.63	0.96
Multi	10	53	11	172	146	32	560	0.60	0.50	0.70
2 4 kv Isolated	2	40	35	45	200	110	285	0+	0+	0+
Uni	2	37	30	44	245	130	360	0.30	0.28	0.31
Multi	3	40	13	55	240	85	480	0 60	0.49	0.69

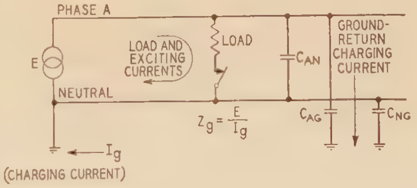
As indicated in figure 2*C*, on a *multigrounded* circuit the loads are in parallel with the capacitance-to-ground and the ground-return components of the load and transformer exciting currents, therefore, add vectorially to the ground-return harmonic charging currents. In the case of multigrounded single-phase circuits having phase and neutral wires of the same size and material and of the usual configurations, about 60 per cent of the phase current returns through the earth and the remaining 40 per cent in the neutral wire. This division holds for the charging current as well as for the load and exciting components.

In the single-phase unigrounded line, large phase displacements occur between the phase wire, neutral wire, and ground-return currents. Consequently the ground-return $I{\cdot}T$ expressed in per cent of the phase $I{\cdot}T$ may range from about 40 to well over 100 per cent. For the fundamental frequency and the lower harmonics, the percentage of phase current returning in the ground is smaller in the unigrounded than in the multigrounded circuit.

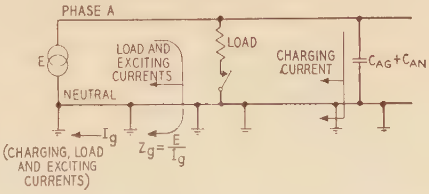
Table II summarizes the average exciting ground-return $I{\cdot}T$ and the individual ground-return current components at 180, 300, and 420 cycles per kilovolt-ampere of connected trans-



(*A*) Circuit consisting of two phase wires



(*B*) Circuit consisting of one phase wire and unigrounded neutral



(C) Circuit consisting of one phase wire and multigrounded neutral

Figure 2. Schematic circuits of single-phase rural power lines

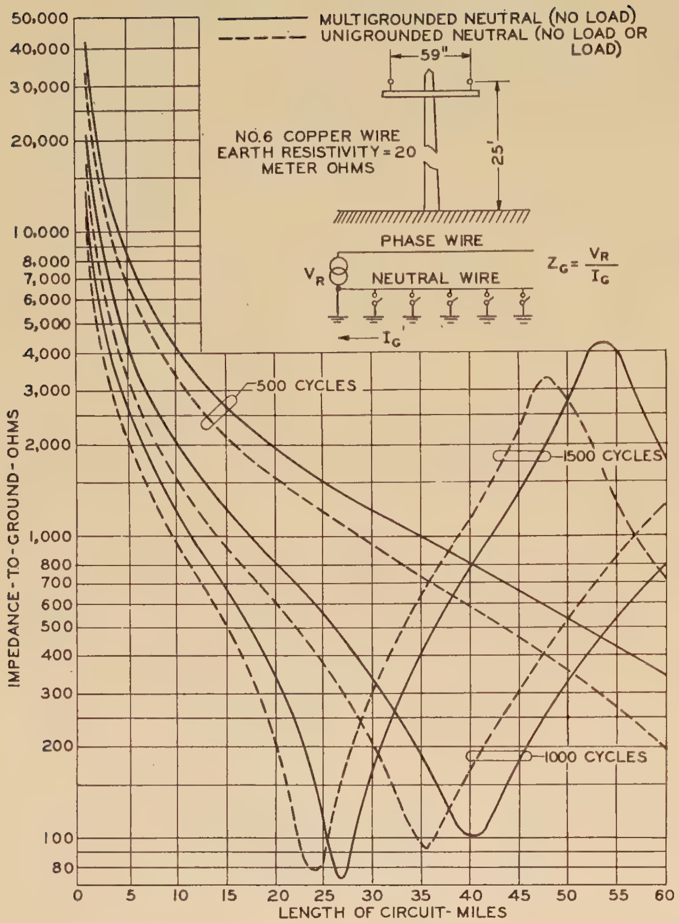


Figure 3. Impedance-to-ground of single-phase power line

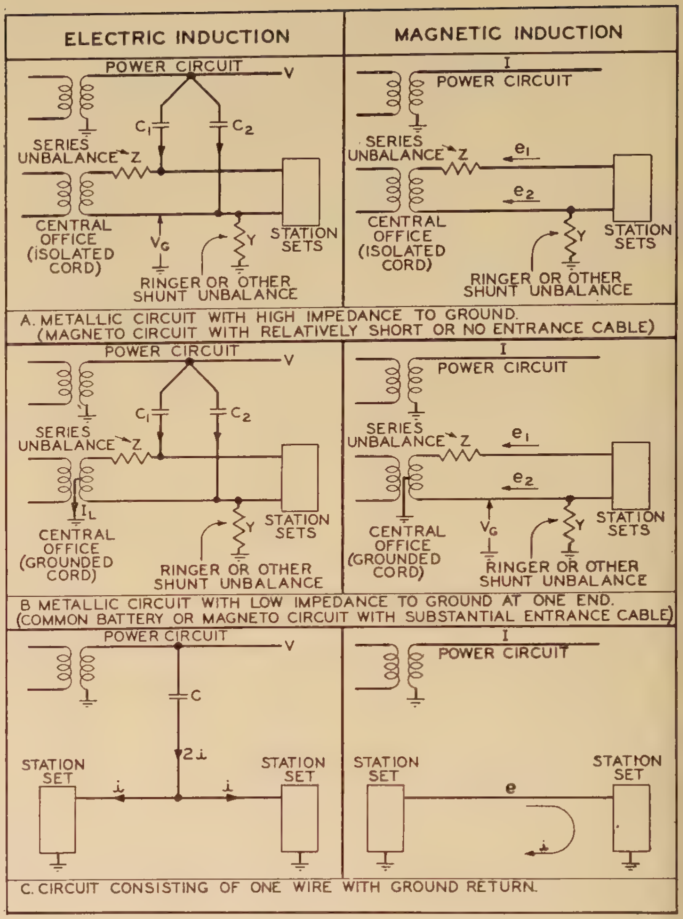

ELECTRIC INDUCTION
MAGNETIC INDUCTION
POWER CIRCUIT
V
I
C_1
C_2
SERIES UNBALANCE
Z
e_1
e_2
CENTRAL OFFICE (ISOLATED CORD)
V_G
Y
STATION SETS
RINGER OR OTHER SHUNT UNBALANCE
A. METALLIC CIRCUIT WITH HIGH IMPEDANCE TO GROUND. (MAGNETO CIRCUIT WITH RELATIVELY SHORT OR NO ENTRANCE CABLE)
I_L
CENTRAL OFFICE (GROUNDED CORD)
B METALLIC CIRCUIT WITH LOW IMPEDANCE TO GROUND AT ONE END. (COMMON BATTERY OR MAGNETO CIRCUIT WITH SUBSTANTIAL ENTRANCE CABLE)
C
2i
i
e
STATION SET
C. CIRCUIT CONSISTING OF ONE WIRE WITH GROUND RETURN.

Figure 4. Schematic diagrams illustrating induction and susceptiveness of rural telephone circuits

former capacity which may be expected on multigrounded single-phase extensions operating at various voltages. These values are based on a transformer having a root-mean-square exciting current of five per cent of the rated full-load current, and increase or decrease approximately in proportion as this percentage is greater or less than five per cent. They are based on average harmonic exciting currents, in per cent of root-mean-square exciting current, of 40, 10, and 2.5 per cent at 180, 300, and 420 cycles, respectively.

The relative magnitudes of the three components contributing to the ground-return $I \cdot T$ of a rural line operated with multigrounded neutral are usually such that the charging currents tend to control on the longer and higher voltage circuits, while the load and exciting current components are apt to predominate on the shorter and lower voltage circuits. For a given impressed residual voltage, the ground-return charging current of a circuit operated with multigrounded neutral is usually somewhat less than that of the same circuit operated ungrounded. Consequently, where the charging current is controlling in the multigrounded case, the inductive influence tends to be less for multigrounded neutral than for isolated or ungrounded neutral operation. Conversely, where load and exciting currents become the controlling factors under the multigrounded neutral condition, the influence is usually greater for multigrounded operation.

The range of ground-return $I \cdot T$ observed on a number of rural lines of various voltages and types is indicated in table III. In this table the ground-return $I \cdot T$ is expressed in terms of the corresponding phase $I \cdot T$. The range of phase $I \cdot T$ and voltage $T.I.F.$ observed in the various systems is also given for reference.

Comparison of Influence of Different Types of Systems

The relative influence under average wave shape conditions of different neutral grounding arrangements for systems of a given voltage class may be summarized as follows:

(1) Three-Phase Systems

In the *6.9 to 13.2-kv voltage range* the inductive influence of an extensive three-phase four-wire rural distribution system with metallically connected single-phase extensions is on the average, about the same for either multigrounded or ungrounded neutral operation. In this voltage range, the influence of the three-phase three-wire delta circuits tested was within the limits observed on multigrounded and ungrounded neutral four-wire systems.

In the *2.3 to 4-kv voltage range* the inductive influence of four-wire multigrounded neutral rural systems is generally somewhat higher than that of four-wire ungrounded or three-wire systems.

(2) Single-Phase Extensions

In the *7-kv class* single-phase extensions connected either metallically or through transformers have a somewhat lower influence for multigrounded neutral operation than for ungrounded operation. Extensions consisting of two-phase wires metallically connected to a three-wire system have an influence comparable to the ungrounded extension.

Extensions in the *4.8-kv class* have generally about the same influence whether operated ungrounded or multigrounded.

In the *2.3-kv class* the influence of multigrounded neutral extensions is generally greater than for those operated ungrounded.

In all voltage classes, extensions supplied through single-phase transformers and operated isolated from ground have a very much lower influence than those operated unigrounded or multigrounded.

It is difficult to make similar comparisons between systems operating in different voltage classes because the different voltage classes tend to have somewhat different fields of application, resulting in differences in line length and load density.

Characteristics of Rural Telephone Circuits

Most of the telephone circuits used in rural areas are of the magneto type, although some common battery lines are encountered. From the noise co-ordination standpoint, there is one fundamental difference between the magneto circuit and the common battery circuit in that the former is generally ungrounded at the central office end, while the latter is grounded through the central office cord circuit. The significance of this difference will be brought out in the brief summary, given below, of the processes by which noise induction takes place. For the sake of simplicity, this discussion is confined to electrically short lines.

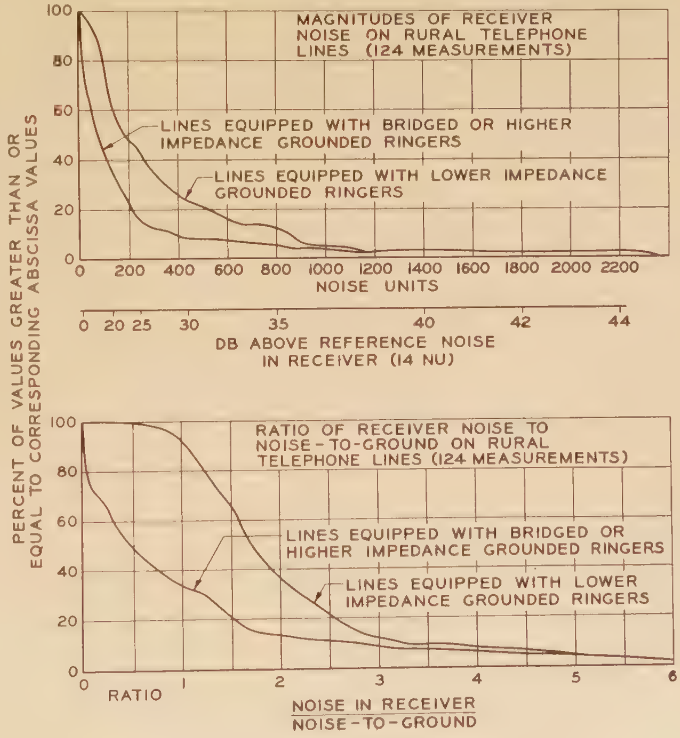
Schematic diagrams illustrating (*A*) an exposed metallic telephone circuit having a high impedance-to-ground and (*B*) a similarly exposed circuit operated with a low impedance-to-ground, are shown in figure 4.

Electric induction appears as a noise potential (V_G in figure 4*A*) between the exposed telephone conductors and ground. This potential is a function of the harmonic voltages on the power conductors, the mutual capacitances C_1 and C_2, and the impedance-to-ground of the telephone circuit. In the case of a telephone circuit isolated from ground, as in figure 4*A*, the noise potential to ground tends to be relatively high, the noise current flowing to ground through the capacitance-to-ground of the circuit. Where one end of the telephone circuit is grounded, as through the cord circuit on a common battery line (figure 4*B*) or through the capacitance-to-ground of an appreciable length of entrance cable, the noise potential to ground due to electric induction may become very small. In this case a noise current (I_L) flows over the two conductors in parallel toward the low-impedance ground.

Magnetic induction appears as a noise voltage (e_1 and e_2, figure 4*A*) acting in the longitudinal circuit of the telephone line. The induced voltage is a function of the harmonic currents in the power line and mutual inductance between the power and telephone conductors. The impedance of the telephone longitudinal circuit controls the magnitude of the resulting longitudinal current. Where the impedance-to-ground is high, as in figure 4*A*, the magnetically induced voltage-to-ground divides between the two ends of the circuit roughly in proportion to their impedances-to-ground. Where one end of the circuit is grounded, the entire induced voltage appears at the other end.

In the case of electric induction, differences in the capacitances C_1 and C_2 result in a difference of potential between the two telephone conductors, thus giving rise to a metallic-circuit noise current known as the "direct metallic" induction. Differences between the magnetically induced voltages e_1 and e_2 similarly result in a "direct metallic" component of magnetic induction. Telephone circuit transpositions tend to equalize the capacitances C_1 and C_2 and the voltages e_1 and e_2 and may thus greatly reduce the noise due to "direct metallic induction."

Figure 5. Noise measured on magneto telephone subscriber circuits in rural areas



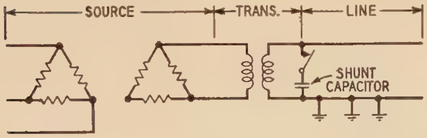
In the case of a ground-return circuit (figure 4*C*) the current-to-ground due to electric induction (*i*) flows directly through the station sets, while the voltage due to magnetic induction (*e*) acts on a longitudinal circuit which includes the impedances of the station sets. This accounts for the fact that the noise in a ground-return circuit is usually of the order of 100 times that in a reasonably well balanced metallic circuit under similar exposure conditions.

In addition to the component of noise induced directly between wires, metallic-circuit noise may also occur as a result of the action of longitudinal induction on circuit unbalances. These may be either series impedance unbalances (*Z* in figure 4) or shunt admittance unbalances (*Y* in figure 4). The more common sources of series unbalances in rural circuits are high resistance joints and certain types of switching circuits used in common battery offices. Shunt unbalances may arise as a result of contacts between line wires and trees, from faulty insulation, from the ringers associated with certain types of station sets where grounded ringing is employed, or from certain types of central office apparatus.

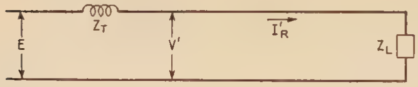
Considering first the effects of electric induction, in figure 4*A*, where the central office end of the circuit has a high impedance-to-ground, the voltage-to-ground appears across the shunt admittance (*Y*) and contributes a component of noise in the metallic circuit. In this case the effect of a series unbalance (*Z*) is small. However, where the circuit has a low impedance-to-ground, as in figure 4*B*, the voltage-to-ground due to electric induction is negligible, and the effect of the admittance unbalance (*Y*) is small. In this case, as pointed out above, the induction produces a current-to-ground and this current acts upon the series unbalance (Z) to produce a metallic-circuit current.

In the case of magnetic induction, the full longitudinal voltage appears across the admittance unbalance (Y) when the circuit is grounded at the central office (figure 4B). If Y is relatively small, the longitudinal current will be relatively small and its effect on the series unbalance (Z) is unimportant. If there is a low impedance-to-ground at each end of the circuit, the longitudinal current may be appreciable, and the effect of (Z) becomes important.

The effects of unbalances may be summarized as follows: shunt unbalances tend to be important where electric induction controls the noise in circuits operated isolated from ground, or where magnetic induction is important, particularly when the circuit is grounded at the central office and such unbalances occur near the far end of the line. Series unbalances may be important where electric induction acts on a circuit grounded at one point, or in the case where magnetic induction acts on a longitudinal circuit having a low impedance at each end. The effects of these unbalances may be minimized by employing higher impedance ringers, balanced central office equipment, and by reasonably adequate maintenance of the open-wire circuits. In some cases special measures, discussed below, may be employed.



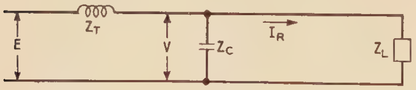
(A) Schematic diagram



(B) Equivalent circuit—capacitor off

Z_T = Impedance of source and transformer

Z_L = Impedance to residuals of line



(C) Equivalent circuit—capacitor on

Figure 6. Shunt capacitors for improving wave shape of rural power lines

The cumulative per cent curves in the upper portion of figure 5 indicate the range of noise observed on a large number of rural magneto telephone circuits exposed to various types of power circuits. No attempt is made to differentiate between the effects of the different types of power systems involved. An indication of the relative influence of these different types of system may be obtained from tables I and III. The effects of the lower impedance ringers in increasing the receiver noise are indicated in figure 5.

The ratio of receiver noise to noise-to-ground (noise current to ground through 100,000 ohms) is frequently used as an index of the balance of a telephone circuit. This quantity has been calculated for the rural circuits tested and the results are plotted in the lower portion of figure 5.

Co-ordinative Measures

Co-operative planning by those responsible for the development and operation of power and telephone systems is important in rural areas as well as in urban and suburban areas.[1] The general co-ordinative measures outlined in the introduction to this paper are discussed in somewhat more detail below. Certain specific measures which may be helpful in certain types of situation are also described. None of these measures is universally applicable. The measure or combination of measures best suited to a given case can be determined only when all the various factors are known.

Power System Measures

One of the factors controlling the inductive influence of a rural power circuit is its wave shape. The problem of co-ordinating rural power and telephone systems is usually simplified if the magnitudes of the harmonics impressed on the power circuits by either the supply or load apparatus are relatively small. One method of improving the wave shape, by means of shunt capacitors, is discussed later.

As previously pointed out, the harmonic exciting currents of single-phase transformers may be of importance in the inductive influence of multigrounded distribution circuits, particularly those operating in the lower voltage ranges. The magnitudes of these harmonic components can be controlled to a considerable extent in both the design and application of the transformers. Tests indicate that there is a rapid increase in the harmonic components of the exciting current of a transformer when the rated fundamental frequency voltage is exceeded. It is therefore desirable to avoid impressing excessive voltages on transformers, particularly when they are connected to the lower voltage multigrounded circuits.

On three-phase distribution systems, reductions may often be effected in the inductive influence if the lengths of single-phase extensions as well as the amounts of single-phase loads are balanced among the various phases in so far as practicable. Field experience has indicated, however, that where relatively large harmonics are present in the voltage wave shape of an extensive system, it is generally impracticable to secure adequate reductions in the ground-return current components of a three-phase circuit by balancing the extensions only, without resorting to reductions in the impressed harmonic voltages.

Table IV. Measured Effectiveness of Shunt Capacitors in Reducing Inductive Influence of Rural Distribution Circuits Supplied from Transformers

Case A—Six-mile multigrounded 7.2-kv single-phase extension supplied through a 25-kva 2.3–6.9-kv transformer. Capacitor connected across 6.9-kv side of transformer.				
Capacitor (Kilovolt-amperes)	None	15		
Voltage $T.I.F.$ 2.4 kv	20	15		
Voltage $T.I.F.$ 7.2 kv	74	5.6		
Phase $I{\cdot}T$ of 7.2-kv extension	390	29		
Ground-return $I{\cdot}T$ of 7.2-kv extension	215	16		
Case B—Thirty-mile multigrounded 6.9-kv single-phase extension supplied through 100-kva 2.3–6.9-kv transformer. Capacitor connected across 6.9-kv side of transformer.				
Capacitor (Kilovolt-amperes)	None	15	20	35
Voltage $T.I.F.$ 2.3 kv	76	36	16	15
Voltage $T.I.F.$ 6.9 kv	118	32	30	16
Phase $I{\cdot}T$ of 6.9-kv extension	2,130	535	480	285
Ground-return $I{\cdot}T$ of 6.9-kv extension	1,120	285	260	163
Case C—Twelve-kv three-phase four-wire multigrounded system (total length 13 miles three phases and 27 miles one phase) fed from 150-kva 13.2–12-kv delta-wye transformer bank. Three-phase capacitors connected on 12-kv side of transformer.				
Capacitor (Kilovolt-amperes per phase)	None	15	30	
Average phase-phase voltage $T.I.F.$ 13.2 kv	20	16	17	
Average phase-neutral voltage $T.I.F.$ 12 kv	58	12	9	
Average phase $I{\cdot}T$—12-kv line	610	90	50	
Ground-return $I{\cdot}T$—12-kv line	360	45	30	

Power circuit transpositions afford an effective means of reducing longitudinal induction in exposed telephone circuits only if the influence is controlled by balanced rather than residual components.[5] In rural distribution exposures the induction practically always results from residual components, and in such cases transpositions are generally ineffective. Furthermore, in the case of three-phase circuits, these residuals are usually due either to the unequal lengths of single-phase extensions connected to the various phases or to direct-connected generators with grounded neutrals and consequently are not susceptible to reduction by transpositions.

Shunt Capacitors for Reducing Inductive Influence

Several situations have recently developed in the field in which the influence of the power lines was considerably increased by resonance between the leakage inductance of the supply transformer and the line capacitance at or near one of the harmonic frequencies present in the impressed voltage. In such cases it has been found practicable to improve wave-shape conditions by the application of shunt capacitors on the rural-line side of the supply transformer.

Figure 6*A* presents a schematic diagram of a single-phase extension supplied from a three-phase system through a single-phase transformer. Figure 6*B* is a simplified equivalent circuit of this arrangement, the voltage E representing the voltage at a given harmonic frequency in the wave shape of the source. Actually there are other harmonics in the system such as those generated by the supply and load transformers, or by certain types of load. However, on rural lines these frequently contribute less to the over-all influence than the supply system voltages and for simplicity have been omitted from the equivalent circuit.

In rural distribution lines, particularly under light load conditions, the impedance Z_L (figure 6*B*) is largely capacitive reactance below the quarter wave length frequency. Consequently, a condition of series resonance will exist at the frequency where the inductive reactance of the source and transformer (Z_T) is equal to the capacitive reactance of the line (Z_L), resulting in substantial increases in the voltages and currents in the rural line at harmonics in the vicinity of the resonant frequency. The connection of a suitable capacitor across the circuit, as indicated in figure 6*C*, will change the resonant point to some lower frequency, thus causing large reductions in those harmonics which were close to the resonant frequency existing before the capacitor was connected. In selecting[2] the size of capacitor for a particular situation it is important to avoid establishing the lower frequency resonant point close to one of the harmonic frequencies present in the voltage wave shape. The shunt capacitor in combination with the transformer leakage inductance also has a filtering action which tends to reduce the higher frequencies where the impedance of the capacitor is small in comparison with the impedance of the rural line.

The degree of improvement in influence effected by the application of a capacitor depends upon the particular harmonic frequencies present and upon such other factors as the relative size of the capacitor and transformer, the length of the rural line, and the magnitude of harmonic components originating in loads. The results of tests of the effectiveness of shunt capacitors in three field situations, the first two involving single-phase extensions and the third a three-phase line, are summarized in table IV. It will be noted that in all cases, before the capacitors were applied, the voltage *T.I.F.* was higher on the line than on the supply side of the transformer due to the resonant condition previously mentioned. Substantial reductions in both voltage *T.I.F.* and ground-return *I·T* were effected by the use of capacitors in these cases.

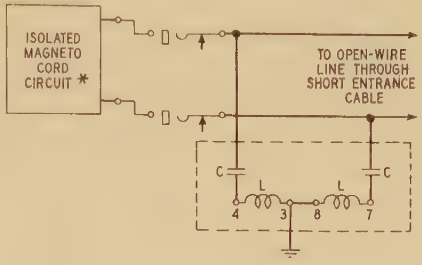
Telephone System Measures

Experience has indicated that the noise in transposed open-wire telephone circuits exposed to rural power lines at roadway separation is apt to be controlled by the action of longitudinal induction on circuit unbalances rather than by direct metallic induction. In cases where the effects of circuit unbalances have been minimized and the telephone circuit transpositions are not co-ordinated with the exposure conditions, improvements in the transposition arrangement should result in reductions in the direct metallic induction and in the receiver noise.

In general, station sets of the multiparty types on rural telephone lines are equipped with the higher impedance type of ringers, particularly where circuits are subject to noise induction. The lower impedance grounded ringer is therefore less likely to be an important factor in the co-ordination problem in rural localities than in urban areas.[1] Since unbalance of any type may contribute to the metallic circuit noise, any measures taken to improve the balance of a rural circuit will be reflected in noise reduction. In some cases the most practicable means of reducing the susceptiveness of the telephone circuits may be the application of the special measures described below.

Drainage on Ungrounded Circuits

As shown in figure 4*A*, the receiver noise on magneto lines which are ordinarily ungrounded at the central office, may be controlled by the action of voltage-to-ground from electric induction on shunt unbalances such as tree leaks or grounded ringers. In such cases substantial improvement in the noise may be secured by the application of drainage at the central office end of the circuit, with the consequent reduction of the voltage-to-ground on the circuit. Drainage is also effective in reducing the 60-cycle induced voltage which is sometimes sufficiently large to cause false ringing of subscribers' bells where grounded ringers are employed. Figure 7*A* shows schematically an arrangement of a balanced retardation coil and a pair of balanced condensers for this purpose. This combination presents a low impedance to the longitudinal circuit, and a relatively high impedance across the metallic circuit. The condensers are provided to permit satisfactory ringing and d-c testing on the circuit. Since

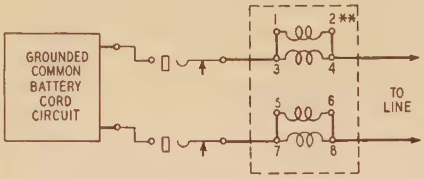

ISOLATED MAGNETO CORD CIRCUIT *
TO OPEN-WIRE LINE THROUGH SHORT ENTRANCE CABLE
C
C
L
L
4
3
8
7

(*A*) Use of drainage on ungrounded circuits (noise controlled by action of longitudinal electric induction on shunt unbalances)

L,L—Balanced retardation coil with midpoint grounded

C,C—Capacitors of approximately one microfarad capacitance

* Drainage also applicable where line is grounded through high impedance



(*B*) Use of high impedance in longitudinal circuit (noise controlled by action of longitudinal magnetic induction on series unbalances)

** Repeating coil connected to offer high longitudinal and low metallic circuit impedance

Figure 7. Special measures for reducing susceptiveness of rural telephone circuits

drainage increases the longitudinal noise current, the use of this low-impedance termination may result in increased noise in cases where important *series* unbalances are present in the telephone circuit.

Where an open-wire line enters an office through an appreciable length of cable, a degree of drainage is provided by the capacitance-to-ground of the latter. Where long entrance cables are involved and the open wire is consequently already effectively drained, little further reduction in noise would be expected from the drainage scheme described above.

Table V. Effect of Drainage in Reducing Noise on Magneto Telephone Circuits

		Noise Measured at Subscriber's Location (Noise Units)		
			Noise in Receiver	
Location	Central Office Terminal*	Noise to Ground	Bridged Ringer	Grounded Lower Impedance Ringer
A	*I*	350	70	450
	G	9	0+	0+
B	*I*	400	85	500
	G	60	65	65
C	*I*	750	210	1,400
	G	15	150	170
D	*I*	210	1,100	1,130
	G	20	160	160

* *I*—Central office end isolated from ground.
G—Central office end grounded through midpoint of balanced termination (figure 7*A*).

Although primarily intended for use on magneto circuits, this drainage device may also find application on common battery circuits where noise results from the action of longitudinal induction on unbalances in the central office. In step-by-step offices, for example, where the impedance-to-ground offered by the central office equipment may be of the order of 1,000 ohms at 1,000 cycles, advantage may be taken of the relatively low impedance of the drainage device to reduce the voltage acting on central office unbalances.

The effectiveness of this drainage device in reducing the noise on magneto circuits at several locations where electric induction controlled is demonstrated by the data summarized in table V.

High Impedance in the Longitudinal Circuit

In the case of common-battery manual circuits there may be relatively large longitudinal noise current flowing to earth through the cord-circuit ground at the central office (figure 4*B*). Where *series* unbalances are present either in the line or in the cord circuit, the component of metallic-circuit noise, resulting from the action of the longitudinal current on these unbalances, may be controlling. In cases where *magnetic* induction controls, considerable reductions in the longitudinal current and consequently in the receiver noise may be effected by inserting an inductance in the circuit, as illustrated in figure 7*B*. This device is so connected as to offer a relatively high impedance to the longitudinal circuit and a very low impedance to the metallic circuit. Increasing the longitudinal circuit impedance frequently increases the noise-to-ground on the circuit. Consequently, a net improvement in the metallic-circuit noise will be obtained by this method only where the effect of *shunt* unbalances is small.

In some cases both series unbalances in office equipment and shunt unbalances on the line may be important. In such instances, use may be made of a combination of the high longitudinal impedance, inserted at the central office, and the drainage device, discussed above, the latter being connected on the line side of the series impedance.

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2. Engineering Report 40 of Engineering Reports of Joint Subcommittee on Development and Research.

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4. Measurement of Telephone Noise and Power Wave Shape, **J. M. Barstow, P. W. Blye,** and **H. E. Kent.** AIEE Transactions, volume 54, 1935, page 1307.

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Discussion

L. F. Roehmann (Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.): The authors suggest the use of shunt capacitors as a means for lowering the inductive influence of power lines. They claim two favorable effects, namely:

1. Detuning the circuit for the harmonic for which it is in resonance, and
2. Short-circuiting other harmonics.

The measurements as shown in table IV indicate that the reductions exceed the ratio 10 to 1, a very satisfactory result.

But this result is accomplished by comparatively large and expensive capacitors (15 to 35 kva), and I wonder whether such expense be justified from the standpoint of noise co-ordination alone.

The aspect becomes much more favorable, however, if the effect on the fundamental is considered too. The capacitors should improve power factor and regulation, both desirable features especially in rural electrification.

I would like to know if the authors have studied this point, and if they can confirm my considerations.

H. E. Kent (Edison Electric Institute, New York, N. Y.): The paper by Messrs. Wahlquist and Taylor has presented the rural co-ordination problem as it affects metallic telephone circuits. I should like to refer briefly to some co-ordinative measures which can be used where ground-return telephone circuits are involved. These are predominately measures applicable to the telephone system, since the measures already described for application to the power system effect approximately the same degree of reduction in influence whether metallic or ground-return telephone circuits are involved. However, it should be borne in mind that a ground-return circuit is inherently of the order of one hundred times as sensitive to induction as is a metallic telephone circuit. Consequently, while the power system measures already described greatly simplify co-ordination with metallic telephone circuits, in many situations additional measures will be required in the co-ordination of ground-return telephone circuits.

The improvement of wave shape by means of capacitors described in the paper is obtained by preventing the higher frequency harmonics in the source of supply from reaching the rural distribution system. In one of the cases where this method was applied it was found that, after the capacitors were connected at the supply substation, various small motors supplied by the rural distribution system still introduced appreciable harmonics, the effects of which were amplified by line resonance conditions. While this was not sufficient to disturb metallic telephone circuits, it resulted in appreciable noise in the ground return circuits. Application of an additional bank of capacitors to the rural circuit at a point about 20 miles from the supply substation destroyed the resonance conditions and effected further reduction in the influence.

Capacitors provide a means of largely eliminating the higher frequency harmonics in many situations, particularly in rural areas. However, it is not feasible to also reduce the lower frequency harmonics (particularly 180, 300, and 420 cycles) by this method. Where these low frequencies control it is possible to improve conditions by reducing the sensitivity of the telephone set in this low frequency range but with no important change in sensitivity over the remainder of the voice frequency range. Two methods of accomplishing this are indicated in figure 1. The commonly used connection for a local battery telephone set is shown in figure 1*A*. This is modified in figure 1*B* by shunting the receiver with an inductance of 60 millihenries and by connecting a 0.75-microfarad condenser in series with the receiver. In figure 1*C* the modification consists of transferring the receiver from the line to a location across the transmitter winding of the induction coil, and adding a one-microfarad condenser in series with the receiver. Field tests in several locations have shown that either of these methods effects reductions in noise of somewhat better than 2 to 1 on the average when the frequencies controlling the noise are in the range from 180 to 420 cycles.

Similar results can be obtained by reducing the acoustical response of the telephone receiver at the lower frequencies. This can be done by punching a quarter-inch hole in the receiver diaphragm at a point one-third the distance across its diameter. Tests have shown that the reduction in the low-frequency noise thus obtained is approximately the same as that secured with the electrical filters. The advantage of the acoustical method lies in its simplicity. It may have some disadvantage from a maintenance standpoint since dirt can more readily enter the space back of the diaphragm.

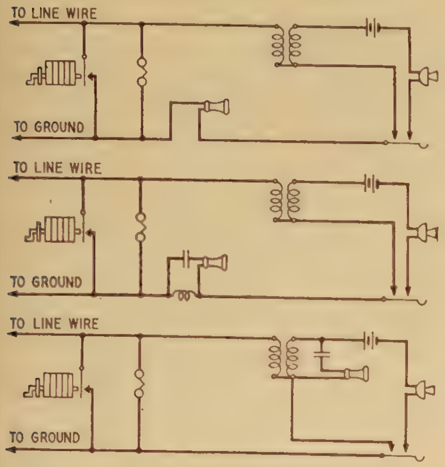

Figure 1. Schematic diagrams of commonly used and modified connections of local-battery telephone set

(*A*) Connection in common use
(*B*) Modification employing receiver filter
(*C*) Modification employing reconnection of set

Figure 2 illustrates the use of a ring-through type of repeating coil in a ground-return telephone circuit to reduce noise by, in effect, transposing the circuit without materially impairing the talking and ringing efficiency of the circuit. The coil acts as a low-impedance drain from line to ground for noise currents resulting from electric induction. For magnetically induced currents the coil acts as a high impedance in series with the line. The effectiveness of the coil depends to a considerable extent on having approximately equal induction in the line on both sides of the coil. In long exposures, particularly where subscribers are distributed through the exposure, more than one coil may be necessary.

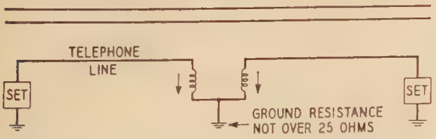

Figure 2. Use of ring-through repeating coil to reduce noise induction in ground-return telephone line

Note: Repeating coil connected as a drainage coil—that is, so as to offer low impedance to equal currents in the same direction in each winding as indicated by the arrows

In individual cases the application of capacitors for the improvement of the power system wave shape combined with a change in the frequency response of the telephone sets, or the use of repeating coils, permits the rendering of reasonably satisfactory rural telephone service over the ground-return line. However, as the load increases on the power line, and more motors are connected, it will become very difficult to maintain the extremely low influence of the power line. This, combined with greater demands made upon the telephone service, may make it impractical to render acceptable service over the ground-return line. Therefore, in applying these measures it must be recognized that in many situations they will offer only a temporary solution of the problem and that ultimately it will be necessary to "metallicize" the line. Of course, in some situations the growth of the service requirements of both the power and the telephone will be such that these measures may last for a number of years. In other situations the growth of the load will be such that continual attention will be required and "metallicizing" will necessarily follow in a very short time.

J. T. Howard (Tennessee Valley Authority, Chattanooga): The authors have touched upon two vital factors contributing to power system influence which seemingly should be given more attention for the benefit of distribution engineers. These are the ground-return harmonic components of transformer exciting currents and charging currents.

Where the rural distribution system is extensive, the voltage at the point of supply is often held 10 or 15 per cent above normal in order to obtain the desired secondary voltage at some distant point without resorting to excessive use of boosters. With distribution transformers working at high flux densities at normal voltage, this increase results in excessive magnetizing current. The net effect is an increase in the $I \cdot T$ product. While it is true, generally, that these components do not control on the larger and higher voltage circuits, many instances have been observed where their effect, in an extensive system, was the controlling factor in noise induction. It appears that placing more emphasis on this point would be of material benefit to distribution engineers, so that they may be guided accordingly in controlling system voltages, and to manufacturers, so that their transformer designs may be modified to allow a better tolerance for overvoltages.

It has been found that the most severe cases of noise induction result from harmonic charging currents, and that exposed communication circuits require a higher degree of maintenance than is customary, if the charging circuit effects are to be minimized. The effects of changes in impedance-to-ground do not seem to be generally understood by distribution engineers, and new systems are designed, and operating systems extended, without any consideration of this factor. In the case of systems operating with an $I \cdot T$ product within the range of average values, extensions may be so connected to the system that resonance occurs at a frequency with a high *T.I.F.* contribution, and the $I \cdot T$ product increases correspondingly. In such event, the distribution engineer is confronted with a difficult task in again co-ordinating his system with exposed communication facilities. It therefore seems desirable that the authors make available, in a concise form, the results of impedance-to-ground measurements which they have made during the past several years, classified as to voltage and configuration. In this manner, the problem of power system influence may be more readily understood.

H. W. Wahlquist and T. A. Taylor: As mentioned by Mr. Kent, the paper is confined to the rural co-ordination problem as it affects metallic telephone circuits and his discussion of several co-ordinative measures applicable to ground-return telephone circuits will no doubt be appreciated by those who are interested in this phase of the problem.

Mr. Roehmann refers to the comparatively large and expensive capacitors used in accomplishing the reductions in influence listed in table IV. While it is true that the kilovolt-amperes of the capacitors was considerable, representing about 15 to 60 per cent of the kilovolt-amperes of the supply transformer, the expense involved was found to be less than that of other co-ordinative measures of equal effectiveness. The use of such capacitors increases the 60-cycle voltage about two to 5 per cent, but has little effect on the voltage regulation of the line. In the case of a rural line having a peak load of low power factor approaching the rating of the supply transformer, the capacitors would be beneficial in reducing the load on the transformer by reducing the reactive kilovolt-ampere.

Mr. Howard feels that more emphasis should be placed on transformer exciting currents as a source of harmonics. While it is true that transformer exciting currents may control the $I \cdot T$ product on rural lines under light load conditions (in cases where the harmonics in the supply systems voltage are relatively small), the magnitude of the $I \cdot T$ product under such conditions is relatively low. On the other hand, in urban areas, transformer exciting currents have in some cases been of importance from the noise standpoint due, among other things, to the heavier load density and to different characteristics of the telephone apparatus. Mr. Howard also expresses interest in impedance-to-ground measurements on power systems. This is an important factor and has received detailed consideration. Methods have been developed for calculating this impedance and have been presented, together with measured results for a few cases, in reference 2 of the paper. Control of the *magnitude* of the impedance-to-ground by special attention to circuit layout does not appear likely to be of much practical importance because operating and service requirements will necessarily govern the system arrangement. However, as pointed out in the paper, it may be feasible to minimize the *unbalance* of the impedance-to-ground among the several phases of a three-phase system by connecting approximately equal lengths of single-phase extension to each of the three phases.

The Wound-Core Distribution Transformer

By E. D. TREANOR
MEMBER AIEE

IN THE very early days of the development of a-c transformers, various methods were tried to produce cores which would have the necessary characteristics of low loss, low magnetizing current, and suitable mechanical arrangements. It was very soon found that the most practical form of raw material was thin iron or iron-alloy sheet which could be obtained with relatively low hysteresis loss, and could be cut and assembled so as to give relatively low eddy-current loss and magnetizing current.

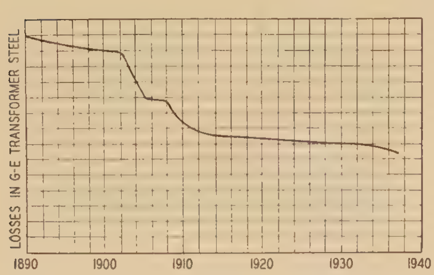

Figure 1. Improvement in hot-rolled magnetic steel

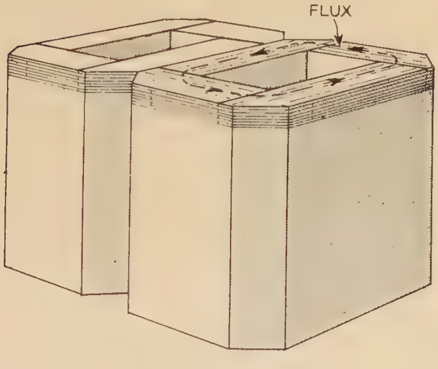

Figure 2. Shell-type core

In this form of thin sheet, magnetic steel for a-c apparatus has undergone years of intensive development from the standpoint of processing and alloying, and steady improvement has made available the silicon steel alloys of excellent characteristics which are in general use today. These are made by hot rolling in packs having maximum dimensions of about three by nine feet. A graphic history of improvement in quality is shown in figure 1.

The mechanical construction of transformer cores has almost universally continued the early practice of cutting plates or punchings from this sheet and building these pieces into massed arrangements of simple or complicated form around the coils. Characteristic examples are shown in figures 2, 3, and 4. Figure 2 shows what is usually called a shell-type core, figure 3 a "core" type, and figure 4 a modified type, which is called the distributed core.

Cores made in this general fashion have certain objectionable features.

(*a*) The pieces cannot be cut and arranged so that the flux path follows the grain orientation of the steel throughout the core and thus obtain the lowest loss possible. Reference to the sketches will show that in figure 2 and figure 3 appreciable parts of the punchings have the grain direction (shown by light lines) lying at some angle with the flux while in figure 4 practically all of the punchings show an angle between grain and flux. Some portions carry no flux at all.

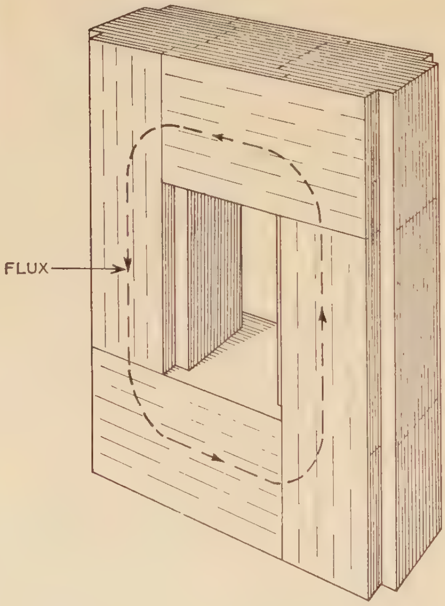

Figure 3. "Core" type core (two legs)

(*b*) The pieces as ordinarily laid up in one or two thicknesses per layer have a minimum of two overlapped gaps in the magnetic circuit (where L punchings are used) and a maximum of four such gaps where straight plates are used. These gaps are dependent in size upon perfection of the pieces and the skill of the workmen, and at best add a little local loss due to fringing of flux and demand an appreciable magnetomotive force, or in other terms, magnetizing current.

(*c*) Large numbers of pieces must be cut and handled through various operations, such as annealing and assembly. Substantial clamping structures must also be used to hold the structure together but without undue pressure. With the usual thickness of 14 mils, not less than 140 pieces per inch of assembled thickness must be used and handled one or two at a time. There is considerable labor cost in these operations.

(*d*) There is at best considerable waste material in the punching and handling operations. In the case of L punchings so largely used on distribution transformers, multiple dies cut punchings from sheets welded together into a continuous ribbon with even less waste than when rectangular pieces are used but there is still an appreciable waste.

The "Wound Core"

A radically new form of core of simple structure and highly efficient performance has recently been developed. As shown schematically in figure 5, it is made by winding a long ribbon of magnetic steel in a tight spiral on a mandrel into the form of a heavy-walled circular cylinder. This core construction has been designated as the "wound core." It eliminates or minimizes most of the objections inherent in other types.

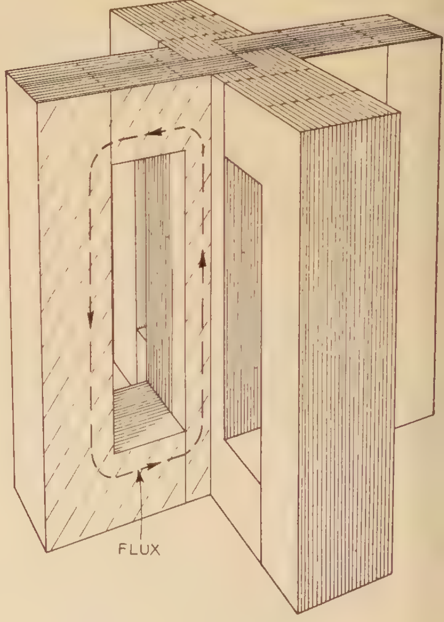

Figure 4. Distributed core

(*a*) The flux runs with the grain direction throughout. All material in the core is active material.

(*b*) There is but one effective gap in the magnetic circuit and this is of very short length and large area.

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(*c*) Only one or two pieces of strip steel are necessary to make the average small core. These are prewound and assembled on machines at high speed.

(*d*) The waste in handling and fabrication is very small since each element is simply cut from large reels of continuous strip made to correct width at the mill.

A practical core incorporating these and other advantages obviously presents a distinct advance in the design and construction of transformers to which it is applicable. It is the purpose of this paper to describe its present application to distribution transformers.

As stated above, L punchings for distribution transformers are cut from reels of steel made by welding together sheets of hot-rolled steel. Distribution transformers of the wound-core construction can utilize such hot-rolled steel with improvement in characteristics and reduction in cost over existing designs, but the wound-core construction makes it possible to take full advantage of the properties of cold-rolled strip of relatively low silicon content. This strip is characterized by high permeability and very good losses at high densities, and is nonaging. It is made by high-reduction rolling on a suitable mill and mechanically is soft and ductile when compared with high silicon hot-rolled sheet. It is produced in a strip of great length.

Figures 6 and 7 show tentative comparisons of watt loss and permeability as compared with good high-silicon hot-rolled sheet. It is strongly directional in these properties, the losses at flux angles with the grain of 45 degrees to 90 degrees being from 45 per cent to 70 per cent higher than with the grain. These properties indicate the possibility of operation at higher densities than are normal with ordinary steel, particularly in a core in which the magnetic material is worked with the grain.

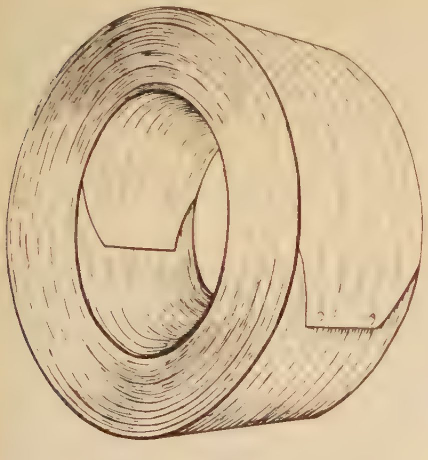

Figure 5. Wound core

Considering a core made up of single ribbon, whose grain direction runs with its length, wound into a circular cylinder and embraced by a current-carrying coil, it will be seen that the flux must follow the grain direction very closely. In such a core (figure 8), it will be seen also that each element of flux finds but one air gap in its path, and if the ribbon is tightly and uniformly wound, this gap will be of very small length and relatively great area. The result is that little magnetomotive force is consumed in the reluctance of air gaps as compared with other cores.

In the practical design of transformer cores, flux density is limited by heating or magnetizing current in large transformers and usually to still lower values by magnetizing current alone in small units. The combination of a steel having high permeability and low losses in the high density range with a core structure which reduces the number and length of air gaps promises highly effective use of material, particularly in small-sized transformers.

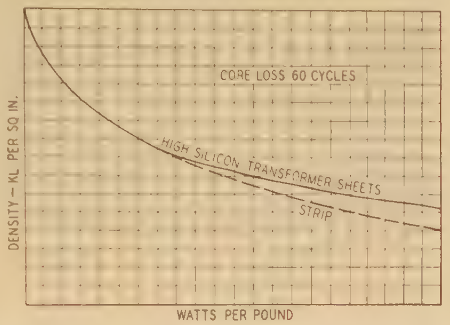

Figure 6. Watt loss of hot-rolled and new strip steel

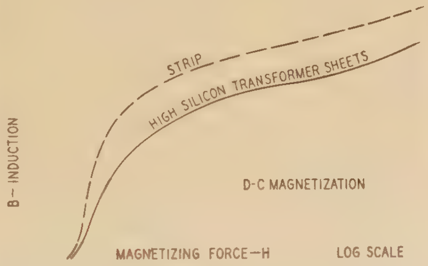

Figure 7. Permeability of hot-rolled and new strip steel

Designs for ratings of $1^1/_2$, 3, and 5-kva units with primary voltages of 7,620 volts or less have been worked out and placed in production, and the promise of economy has been fully realized. The most satisfactory construction consists of two core elements as shown in figures 9 and 10, linked by a simple interleaved coil group in secondary-primary-secondary arrangement. Due to the ability to work the core at higher density than is usual for small transformers, normal characteristics can be obtained with considerable economy of material and reduced over-all cost in spite of the fact that the new steel is at present higher in cost than hot-rolled silicon steel.

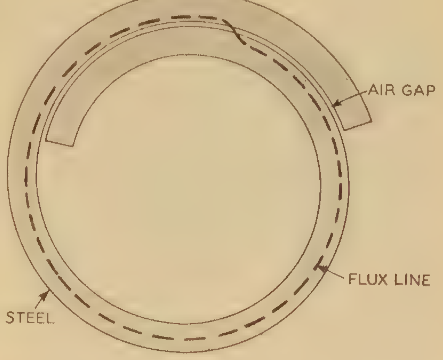

Figure 8. Path of flux in wound core

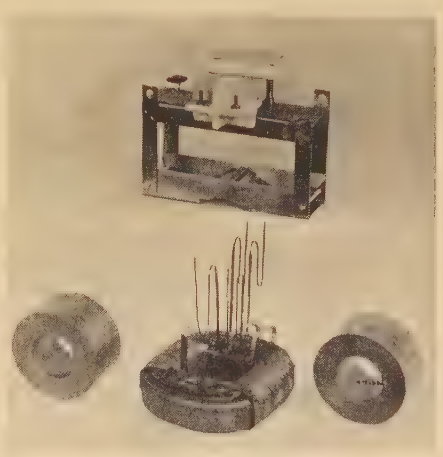

Figure 9. Core and coil elements

Core Manufacture

The steel for wound cores is produced at the mill in strips of required widths and great length. These strips are slit into multiples of desired width for various size cores and are shipped in reels of a convenient size and weight to the factory. These reels are set up in multiple before a prewinding machine which consists of an accurately sized power-driven steel mandrel. The ends of the reels are attached to the mandrel which is then rotated, drawing the strips through tension devices until the cores are built up to the desired thickness which is individually controlled by micrometer gauges. Each strip is cut and temporarily welded to hold the core in shape during anneal. The whole operation is, of course, quite rapid as compared with cutting and stack-

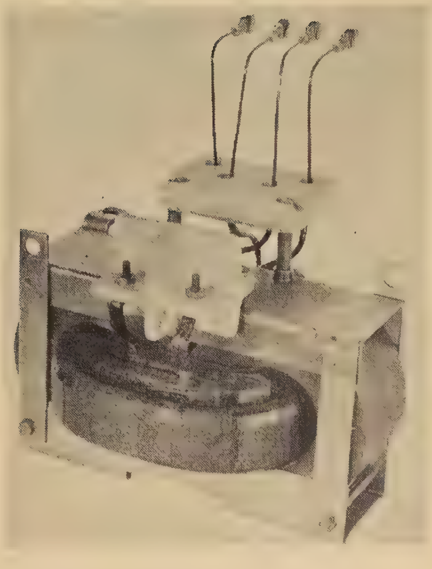

Figure 10. Core and coil unit with clamps and terminals

ing the hundreds of individual punchings which would be required to make equivalent cores of the old type. The space factor of the wound core is materially higher than with assembled punchings, reaching values of 95 per cent to 96 per cent.

The cores are annealed through a cycle which has been developed for this new material and are then delivered to the assembly room. It should be noted that the equipment necessary for putting the core into shape for assembling consists of a single core-winding machine as against an otherwise large investment in heavy high-speed punches and punching dies. The operation of gathering and stacking punchings for anneal is eliminated and several operations of grouping punchings by weight and number after anneal are eliminated.

Coils

The coils for these small transformers are of more or less normal design. They are of oval shape and short axial length. The inner and outer low-voltage coils are of shorter axial length than the high-voltage coils so that when assembled in a low-voltage-high-voltage-low-voltage group, a cross section of the group is of cruciform shape to conform to the circular window of the core. The internal insulation of the coils is similar to that which had been highly developed in past practice. The major insulation consists of mica pads between high and low-voltage windings taped on with varnished cloth and the entire group is taped and reinforced where it passes through the core. Where necessary for insulation or thermal requirements, ducts are placed between or within the coils. The corner ducts between the cruciform coil and the circular core provide satisfactory ventilation under the core and the remainder of the coil is fully exposed to the oil.

The arrangement and design of the coils is such as to give good transient voltage distribution and since the cores are applied under tension, the coils are firmly gripped and held in position against mechanical forces of short circuit. In these small units, no other mechanical bracing for the coils is essential.

Method of Assembly or Linkage of Cores With Coils

The two core units necessary for one transformer and its coil group are brought

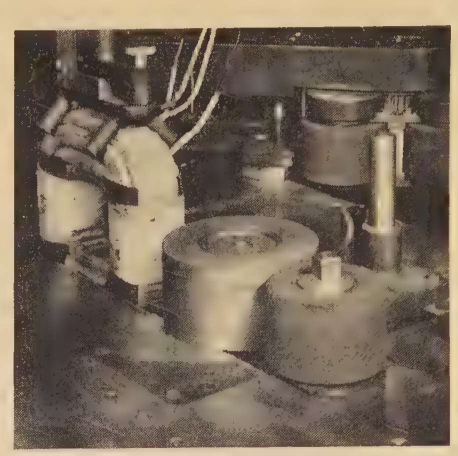

Figure 11. Wound core and coil ready for assembly

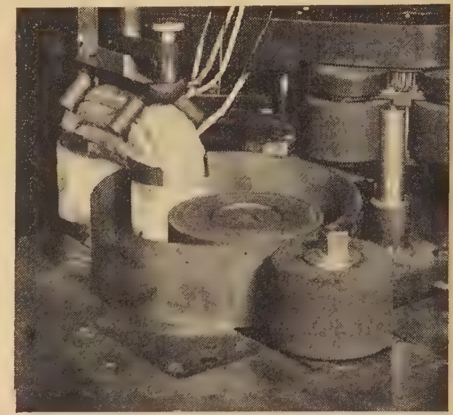

Figure 12. First operation

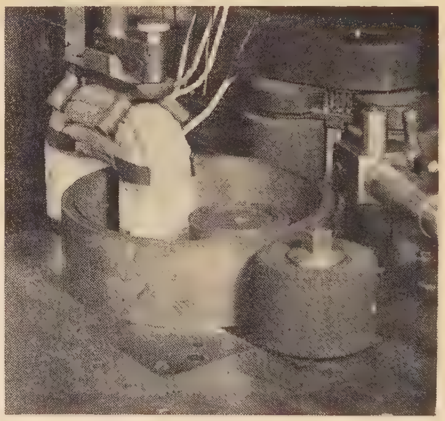

Figure 13. Annealed core partially unwound

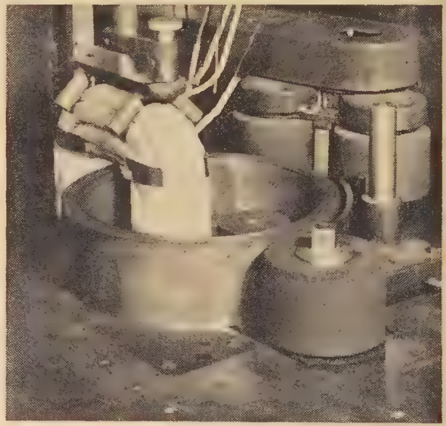

Figure 14. Annealed core completely unwound

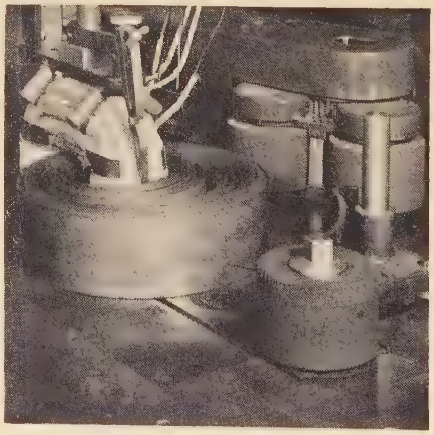

Figure 15. Wound core in loose spiral around coil

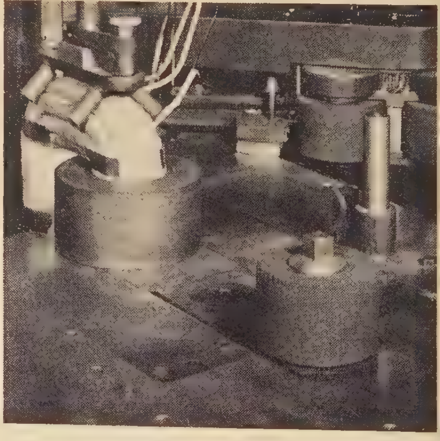

Figure 16. Wound core tightly wound around coil

to a machine which has been developed for the operation of applying cores. The coil group is clamped between cushioned supports on this machine and one core unit is laid beside it over a short power-driven spindle (figure 11). The relative positions of the core and coil are properly adjusted and the welds which secure the outer end of the core strip broken. This outer end is then carried through the coil window in a large loop and temporarily secured on itself so as to form a circle embracing the coil leg (figure 12). A friction roller on the outside of the core and the internal spindle then rotates the core in such a fashion that its entire length is thrown out into a large cylinder embracing the coil leg (figures 13 and 14). The spindle within the core is removed and the core collapses into a loose spiral embracing the coil leg (figure 15). The temporary attachment on the outer turn is now broken and the turns of the loose spiral are drawn inward on the coil leg by power-driven friction rollers applied at its perimeter, with the result that the core is now linked with the coil leg in essentially the same condition as before the operation was begun without having been overstressed during the operation (figure 16). The other core unit is similarly applied to the other leg of the coil group. The outer ends of the strips are welded to permanently secure the cores in shape, and the core and coil unit is ready for clamping, treating, and assembly in the tank. The operations described are rapid and somewhat less dependent on the skill which is necessary to obtain good joints and compact construction in a core made of cut punchings. The machines used at this point are an added investment since cores made of punchings are usually assembled by hand labor.

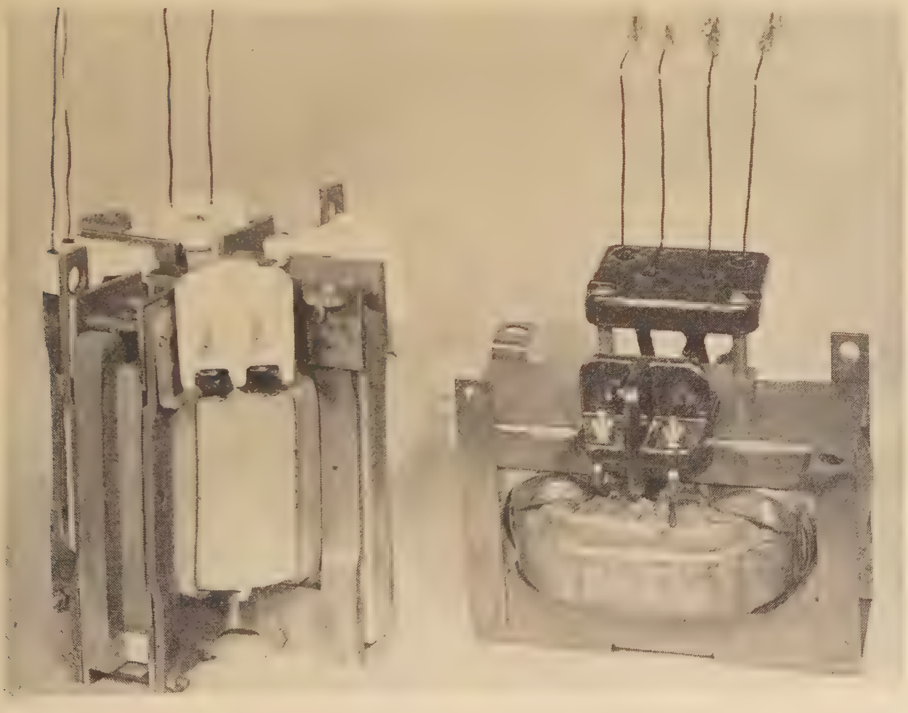

Figure 17. Transformers of distributed-core and wound-core construction

Clamps

Clamps are simple cradles of relatively light steel adapted to grip the cores securely and without distorting them. The structure of the cores is inherently solid and self-supporting.

Characteristics

In over-all characteristics, these transformers have been designed for characteristics which differ only slightly from previous values. In recognition of the importance of improving regulation, the copper loss of the wound-core transformers has been reduced and the core loss slightly increased. This revision of losses seems to be better suited to average operating conditions throughout the country than previous values. The exciting current is lower than with past transformers for reasons given earlier in this paper.

The wound-core distribution transformers, because of a marked reduction in the amount of copper and core iron used, and because of the lighter and simpler clamping structure required, are appreciably lighter in over-all weight than similarly rated units using the conventional core arrangements (figure 17).

Since the difficulty in serving small loads in areas of low density is largely economic, the development of a material and a construction which permits reduction in the price of one important element in the cost of distribution would seem to constitute a major contribution to the broader use of electricity.

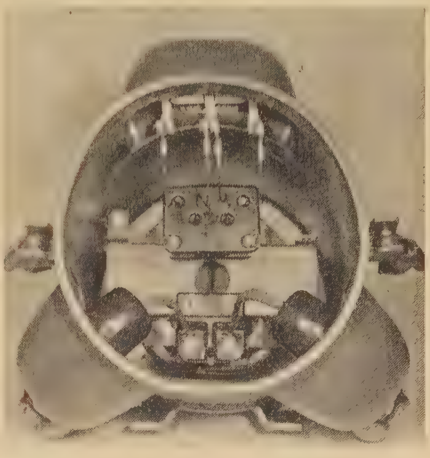

Figure 18. Wound-core unit assembled in tank

The writer wishes to acknowledge the assistance of others in the preparation of this paper, particularly of Mr. J. C. Granfield, the inventor of the wound-core construction, the method of assembly, and the machine, and Mr. M. Broverman who has closely followed the development.

Discussion

Philip Sporn (American Gas and Electric Service Corporation, New York, N. Y.): The distribution transformer, as is well known, plays a very important part in distribution economics. In some phases of distribution, for example in the problem of extension of rural service, it plays an almost predominating part. Here the transformer with its associated equipment represents from 35 per cent to 40 per cent of the average cost of a rural extension, taking for an average an extension in which from four to five transformer installations to the mile are made. Hence I think all electric utility and transmission and distribution engineers will welcome the development described by Mr. Treanor.

In reviewing the work that has been accomplished over the last decade in improving the characteristics and reducing the cost of the distribution transformer, it needs to be recalled that the present distribution-transformer design is basically a development and refinement of an idea that is

Radio Influence Characteristics of Electrical Apparatus

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MEMBER AIEE

C. V. AGGERS
NONMEMBER AIEE

Synopsis: Experience recorded in this paper with the method of measuring the radio influence factor of electrical apparatus recommended by the Joint Co-ordination Committee on Radio Reception of Edison Electric Institute, National Electrical Manufacturers Association, and Radio Manufacturers Association establishes its practicability and adequacy. This method fulfills the essential feature of all working standards in that the results are reproducible by quantitative measurements.

Various types of output meters for determining the radio influence factor of apparatus have been investigated. For practically all applications, the present type of output meter gives an indication which is sufficiently close to the audio output. This characteristic, besides the additional advantages it has in simplicity and relative inexpensiveness, well justifies its use.

Radio frequency influence factors vary in character, depending on the electrode insulation arrangement of the source, and also the dielectric medium.

Humidity and relative density of the air affect the radio influence factor and accordingly certain correction factors for the atmospheric conditions need be recognized.

The radio influence factor characteristics of insulation in air and oil, reported in the paper, establish that normally only apparatus in air need be considered for the effect of radio noise influence, as in co-ordinated apparatus design the strength of parts in oil will exceed those in air.

Experience has shown that quantitative data are essential for this type of study. Since adequate methods of measurements are available, the next step is the establishing of economical levels, which can only be obtained through the co-operation of all interested parties, by the collection of essential field data.

THE operating principles governing radiobroadcasting and reception are generally well-known. Good reception is possible from a radio receiver of suitable characteristics, provided adequate consideration is given to the receiving antenna and provided the field strength from the broadcasting station is sufficiently high. There are many factors detrimental to good radio reception. The signal may suffer distortion, undue weakening, or even complete obliteration at times from the effects in the transmitting medium and in the complex process of propagation of the signal.[1,2] Atmospheric electrical discharges and lightning superimpose their disturbances on the signal and may interfere partially or completely with reception over wide areas.[3] Another source of interference may be contributed from electric power systems and in fact from the very household electrical appliances, which, along with the radio receiver, are contributing to the conveniences and leisure in the modern home. The problems involved in securing good radio reception are therefore many and complex.

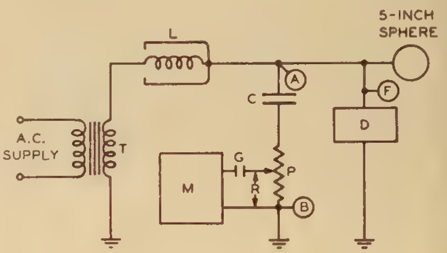

Figure 1. Recommended EEI-NEMA-RMA circuit for determination of radio-noise influence of high-voltage apparatus

T—Testing transformer
L—Radio-frequency choke, shielded, not less than 6,000 ohms reactance at broadcast frequencies
M—Radio noise meter
C—Coupling capacitor, not more than 60 ohms reactance at broadcast frequencies
G—Dummy antenna capacitor (21 micro-microfarads)
D—Device under test
P—Potentiometer or tapped resistor, 600 ohms resistance, nonreactive

This paper deals with the radio influence characteristics of electrical apparatus. As clearly defined by the Joint Co-ordination Committee on Radio Reception of EEI, NEMA, and RMA, improved broadcast reception is essentially a problem of co-ordinating the newer use of electricity and some of its older uses for light, heat, power, transportation, and communication. Accordingly after some years of experience and study this co-ordination body recommended suitable methods of measuring the radio influence factors of electrical apparatus.[4] This procedure naturally has unified effort, stimulated investigation of the problem, and it has made possible the progress which has already been achieved. The investiga-

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1. For all numbered references, see list at end of paper.

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some 35 years old. Hence toward the last ten years the refinement and improvements that have been made have all been of a minor and detailed nature. In other words the vein in which distribution transformer designers were working was getting pretty thin. The development described by Mr. Treanor opens up a very definitely new vein. It shows very strikingly that only by using material and labor more effectively can costs be reduced in the long run. In opening up a new field for reducing both of those items Mr. Treanor and his associates have every reason to believe they have brought about a first class achievement.

It seems to me that the above is the outstanding phase of the development and that that is more important than some of the details as to how the characteristics of the particular steel that is utilized in the new design are obtained or how the ingenious arrangement for winding with so little labor the cores and placing them on the transformer has been worked out. The writer, and I feel certain many others who have been working in the field of improving distribution economics and reducing the cost of distribution of electric service, are looking forward to an intensive development of this vein and possibly to the opening up of new veins and the application of some of the economies already made possible on lower-sized transformers to larger distribution sizes where, if the need for reduction in costs is not as urgently pressing as it is in the field of smaller sizes, it is still nevertheless a major problem. There is no question that distribution costs can stand further reduction, but the distribution engineer needs material help from those who are spending all their energies in the field of designing and building the distribution equipment, the cost of which has a major influence on the whole problem of distribution economics.

E. D. Treanor: We feel with Mr. Sporn that the "vein" had been getting thin with conventional designs in spite of continued improvements in hot-rolled steel and that there is hope for a considerable extension on the new level. Initial progress may be slow but experience with the small units described inspires confidence that further effort along this line will be successful.

tion reported here fulfills further the aim and objectives of the Joint Co-ordination Committee in Radio Reception in establishing new data, findings, and principles that will be of assistance in the radio co-ordination problem.

Measurement and Testing Technique

The test circuit recommended by the joint co-ordination committee[4] for measuring the radio-noise influence factor of high-voltage apparatus is given diagrammatically in figure 1. The characteristics and adequacy of this method of measuring radio noise already have been dealt with to a considerable extent in the technical literature.[5] Its practicability has well been proved by the experience with the first installations and the design of recent installations. Two widely separated laboratories for measuring the radio-noise influence factor of high-voltage apparatus are shown, respectively, in figures 2*A* and 2*B*, and in figure 3. These installations comply essentially with the established recommendations. A brief description of the design characteristics of one installation will illustrate some of the more pertinent principles.

The physical parts of the installation which correspond to the circuit elements in figure 1 are indicated on the photographs. The possibility of appreciable or even measurable radio noise from the circuit proper was eliminated by the use of a $1\frac{5}{8}$-inch diameter rod, five-inch diameter spheres at the ends, and adequacy of all apparatus parts. Special connecting links assembled from large-diameter rods and hemispheres are employed to connect the object under test to the circuit. A 50-kv testing transformer with regulator control supplies the required voltage over the entire range. The room was shielded with metal sheets spot-welded together and solidly connected to a grid system of large strap conductors and driven rods which comprise the ground. Power to the laboratory is supplied over a several-hundred-foot cable from a small transformer station which feeds as additional load part of the lamp circuit in the large plant nearby. By these measures in shielding the room and care in the choice of power supply, background and other interference from external sources were negligible, although immediately adjacent to the radio-noise laboratory is located a 3,000,000-volt impulse generator and also a high-current generator. The attainment of freedom from external noise sources is a feature which illustrates again the advantages and practicability of the recommended method.

The capacitance (C = 0.0021 microfarad) of the coupling capacitor and the effective inductance (L = 12 microhenries) of the drop lead are tuned to 1,000 kilocycles. The ratio of the radio-frequency voltages produced by the object under test on the measuring circuit and the recorded voltages appearing across the terminating resistance is essentially unity over the entire broadcast frequency range as is shown experimentally and by calculation in figure 4. This feature is a desirable one to attain.

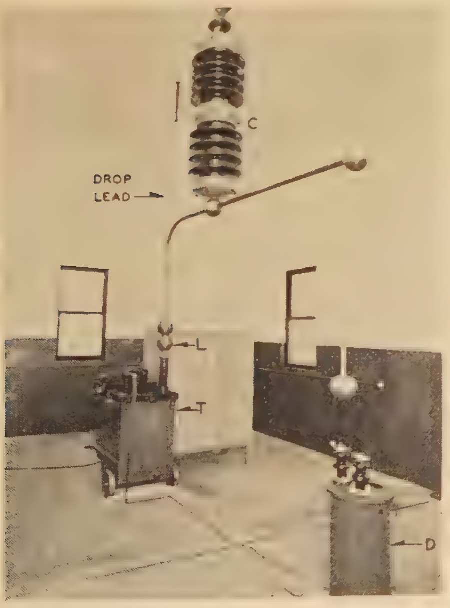

Figure 2A. View of Sharon laboratory

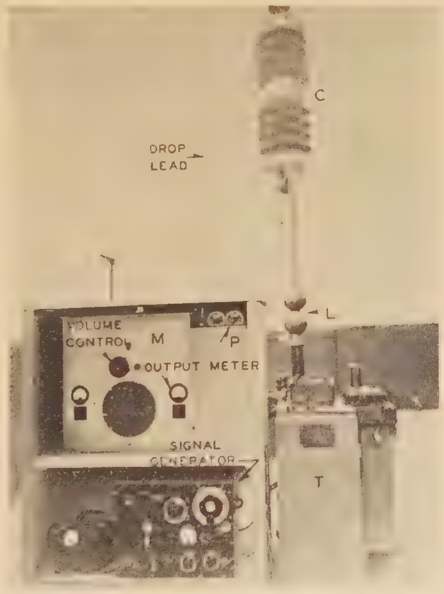

Figure 2B. View of Sharon laboratory

Figure 3. View of East Pittsburgh laboratory

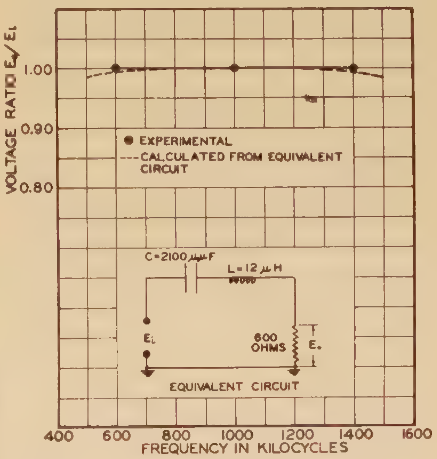

Figure 4. Characteristics of installation in figure 2

Calibration of the radio-noise meter is made by means of a high-frequency signal generator modulated 50 per cent at 400 cycles. The indication on the output meter from the unknown voltage is adjusted to half scale by a volume control on the noise meter. The signal generator is then switched on and its output varied until the same deflection is obtained on the output meter. All radio-noise measurements are therefore based on the signal generator and are microvolt root-mean-square values. The tests are usually made at 1,000 kilocycles which is midway in the broadcast frequency range.

A typical set of tests, showing in figure 5, was made to correlate the measurements at the two laboratories. In test *A*, a rod to plate was employed; this electrode arrangement has served well as a "reference standard" in these and other comparative tests. Tests *B* and *C* were made on electrical equipment. The same samples of the equipment were tested first at one and then at the second laboratory. It should be noted that the laboratories are nearly a hundred miles apart. Though each conforms with the recommended method, they differ from each other in a number of details as

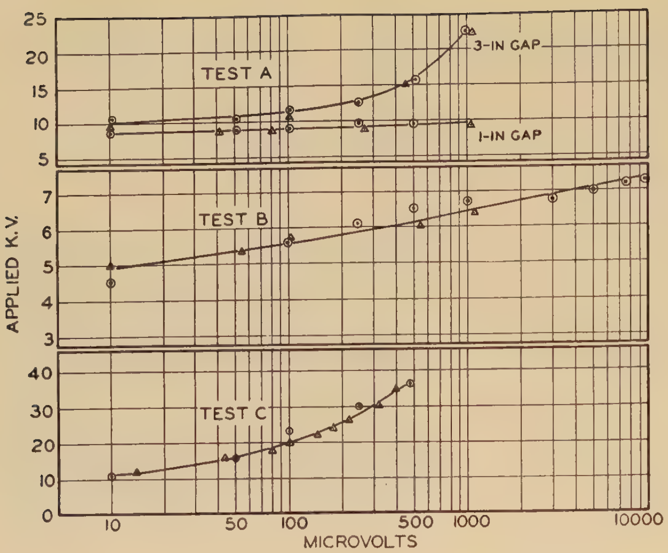

Figure 5. Correlation tests of two laboratories

shown by figures 2 and 3. The East Pittsburgh laboratory, figure 3, is the older installation and has a higher voltage rating. Again using the rod-to-plate arrangement, tests were repeated at various times at Sharon, figure 2. The results are plotted in figure 6 and similar data appear in figure 9. It is clearly apparent from the good agreement in all these tests that the recommended method of measuring radio noise fulfills the essential feature of all working standards in that the results are reproducible by quantitative measurement.

Other Factors in Testing Technique

Measurements were made on a pin-type insulator and on a rod-to-plate gap at various frequencies over the broadcast frequencies. The results are given in figure 7. These and similar tests indicate that the radio-noise influence factors decrease with increase in frequency. The experience up to the present time in testing high-voltage apparatus shows that a relatively uniform decrease in radio-noise influence factors is obtained over the entire broadcast range with no tendency in peaking of radio noise at one frequency. For this reason it appears that the practice in testing at some frequency midway in the broadcast band, such as 1,000 kilocycles, is justified.

The character of radio noise may differ considerably, depending on its generating source. Thus an important feature of the curves for the air-insulated (dry type) apparatus in figure 5 is the uniform continuity in the microvolt rise with increase in applied voltage. Physically the phenomena in these cases is one of uniformly increased radio interference factor with voltage. That the radio interference factor is sustained and uniform was evidenced also from the steady indications of the output meter. Distinctly different from this was the radio noise measured from a sphere to plate. As shown in figure 8, corona and spark-over for this electrode gap occur simultaneously up to about 3.5 sphere-diameter spacing. At the wider spacings corona appears before spark-over voltage is reached. From the visual and aural observations the corona is brusque, in the nature of streamer formation. In fact, the microvolt curves in figure 8 confirm this initial relatively intense discharge, as the lowest measurement that could be recorded is approximately 500 microvolts. The intermittent streamer discharges account also for the unsteady behavior of the output meter in these tests. A similar performance was recorded for the rod to plate above 25 kv where a discontinuity in the curve (figure 6) appears. In short, the two distinct types of corona effects referred to, well illustrate the different character of radio noises that may be encountered.

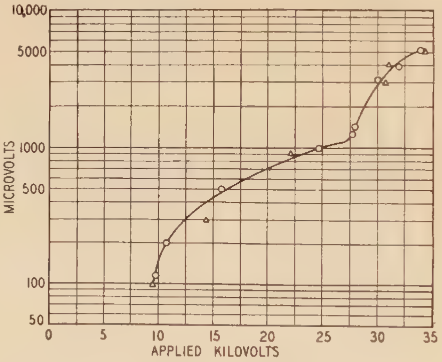

Figure 6. Comparative tests at one laboratory

Rod-to-plate gap; three-inch spacing

Other factors that need be taken into account in radio-frequency testing are the density and humidity of the air. It is recognized that breakdown and corona voltage both depend upon the relative air density and the absolute humidity. In general, the amount of correction for variation of the air density is small. Fundamentally, in radio-interference work this correction would appear to be proportional to the air density, the same as applied to voltage breakdown. Due to the fact that the effect of absolute humidity in high-voltage testing is relatively greater than the relative air density, it appeared desirable to determine its effect on radio-frequency testing.

Tests were made at one of the laboratories where by virtue of the enclosed room the absolute humidity could readily be controlled. First the tests were made at a low humidity. A certain amount of steam was then injected into the room and the air kept well stirred up until the higher humidity was uniformly attained in the room. The tests were repeated. Thus the testing at the two humidities and with identically the same test setup was completed in an hour or less. Results for the rod to plate are given in figure 9. These data have been confirmed by other tests. This investigation establishes that for the rod to plate and for similar electrode arrangements the voltage corresponding to a given radio noise value increases with the absolute humidity 1.5 to 3.0 per cent for each grain per cubic foot. On the average the increase is 2.5 per cent over the entire range in figure 9. This variation in humidity correction factor for radio noise is substantially the

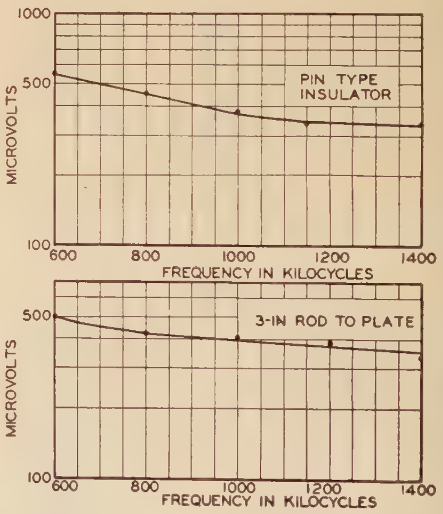

Figure 7. Comparison of tests over the broadcast range

Relative air density = 0.98
Absolute humidity = 4.4 grain per cubic foot

same as that applied to 60-cycle flashover of rod gaps and suspension insulators.[6] Below the very low values of 50 to 100 microvolts the microvolt correction for humidity becomes insignificantly small.

Comparison of Noise Meters

The Joint Co-ordination Committee on Radio Reception of EEI, NEMA, and RMA have formulated specifications for a radio noise meter. These specifications were formulated at the time when tuned-radio-frequency receivers were the most commonly used but since that time the designs of the radio receivers have changed considerably. The selectivity curves of radio receivers are a major characteristic which affects the response of radio receivers to extraneous noises. While the tendency in the past has been toward greater selectivity, the demand for higher fidelity in recent years has required the manufacturing of less selective receivers. Although the specifications for the radio-noise meter were formulated in 1931, no changes in these specifications have been found necessary.

Table I. Selectivity of Three Receivers

Receiver	Band Widths (Kilocycles) Versus Signal Ratio					
	600 Kc		1,000 Kc		1,400 Kc	
	10/1	100/1	10/1	100/1	10/1	100/1
A	12	24	18	37	31	64
B	10	17	9	15	9	19
C	12	22	21	40	27	59

In order to determine the relative response of three different radio instruments that are being used in the laboratories for measuring radio-frequency influence factors, radio-frequency voltages of different character were measured with the three instruments. Two of these instruments are of the tuned-radio-frequency type; the third is a superheterodyne receiver.

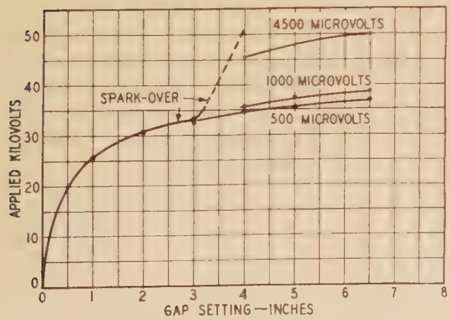

Figure 8. Sphere-to-plate tests illustrating character of radio noise

Two-centimeter sphere to plate

The curves in figure 10 show the results of these three receivers when measuring the radio influence factor from a rod to plate gap separated three inches. This type of noise has produced the greatest deviation between receivers. Figure 11 shows the results when measuring the radio-influence factor from a pin-type insulator. It should be noted that the superheterodyne receiver *B* indicates a value of noise which on the average falls between the two tuned-radio-frequency noise meters.

The selectivity curves of all receivers are shown by table I and it is interesting to note that although the superheterodyne receiver *B* is highly selective at 1,000 kilocycles, the results obtained by this instrument are relatively close to the tuned-radio-frequency instruments. The maximum deviation that has been noted in the values indicated by the three instruments has been slightly over two to one. These instruments do not always maintain the same relative position as shown in figures 10 and 11. In some cases, receiver *B* will measure less than receivers *A* and *C* but always within the deviation limits given above.

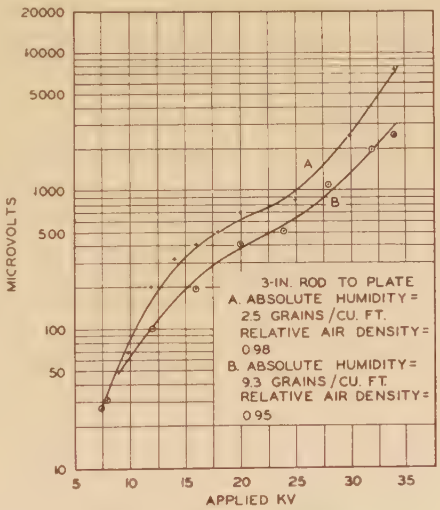

Figure 9. Effect of humidity

Instruments *A* and *C* correspond to the specifications formulated by the Joint Co-ordination Committee on Radio Reception. The output of instrument *A* is highly distorted for values of interference above 1,000 microvolts. This distortion does not exist in either the superheterodyne receiver *B* or instrument *C* up to values in the order of 20,000 to 30,000 microvolts. Repeated tests have indicated that the higher values measured by instrument *A* are in error. A potentiometer is now being used with instrument *A* so that all voltage measurements are made below 1,000 microvolts. With this arrangement consistent results are obtained between the three instruments.

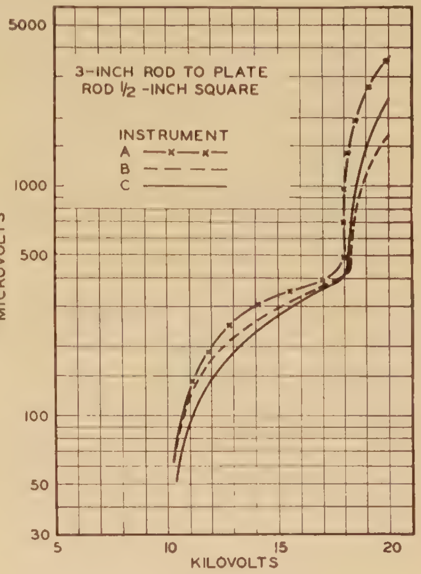

Fig. 10. Comparison of radio-frequency voltages measured by three instruments (tests on rod gap)

Relative air density = 0.99
Absolute humidity = 3.5 grains per cubic foot

Instruments *A* and *C* are battery-operated radio-noise meters. Because of the continuous service required and due to the fact that the superheterodyne receiver incorporated a loudspeaker, it was used in obtaining a portion of the data presented in this paper. It is not advocated however to substitute any radio receiver for the recommended radio noise meter unless facilities are available to determine the relative merits.

Output Meter

The joint co-ordination committee specifies that the output meter for the radio-noise meter should be a critically damped instrument having an undamped period of one-half second. The present noise meters have a Rectox-type output instrument which gives an average value of the radio interference voltage. There has been and probably will be in the future more or less criticism of the output instrument specified by the Joint Co-ordination Committee on Radio Reception. The problem of selecting such an instrument is similar to that which has been encountered by committees in standardizing on a sound level meter. Some feel that the meter should be faster, others feel that the output meter should be over-damped. Still, others advocate

Table II. Radio-Frequency Voltage and Noise Measurements

Voltage Applied Rod Gap (Kilovolts)	Output Meter** Milli-amperes	Micro-volts	Noise Level (Decibels)		Noise Intensity (Micromicro-watts)	Noise Loudness
			(40)*	(80)*		
16.6	0.1	680	75	75	3,200	11,750
20.0	0.2	940	80.5	80	11,250	17,000
20.7	0.3	1,150	82	82	16,000	19,500
22.0	0.4	1,300	84.5	84.5	28,300	24,000
23.5	0.5	1,400	85.5	85.5	36,000	25,000
25.8	0.6	1,550	87	87	50,000	28,500
27.0	0.7	1,700	87.5	87.5	56,000	30,000
27.3	0.8	1,820	90	90	100,000	37,000

* Forty and 80 decibel equal-loudness contours.
** Volume control of noise meter (instrument *B*) at 45 on dial. Microphone one foot directly in front of the loudspeaker.

using a crest instrument for measuring the radio-frequency voltages produced by various devices. It is apparent that some difficulties in measurement will be encountered regardless of the type of output meter. Consequently, the instrument which is the most effective for measuring the radio-frequency voltages from the largest number of electrical apparatus or devices encountered, should be used.

It was realized that the crest voltage produced by the majority of electrical devices or apparatus would not compare favorably with the loudspeaker response. Consequently, it was felt that an averaging tube voltmeter, such as is being used for monitoring broadcasting stations (figure 12) might be an adequate compromise between measurements of peak values of noise by the grid bias and measurements of average values with a highly damped and slower instrument as recommended by the joint co-ordination committee. An investigation was conducted in the laboratory to determine the performance of this average tube voltmeter (figure 12) as compared to the Rectox-type output meter. This average tube voltmeter circuit is such that peaks of duration between 40 and 90 milliseconds are indicated to 90 per cent of full value and the discharge rate adjusted so that the pointer returns from full reading to 10 per cent of zero within 600 milliseconds. The speed of the indicating meter is such that the time for one complete oscillation of the pointer is 290 to 350 milliseconds. The damping factor is such that the overswing is not less than one-half per cent or more than six per cent.

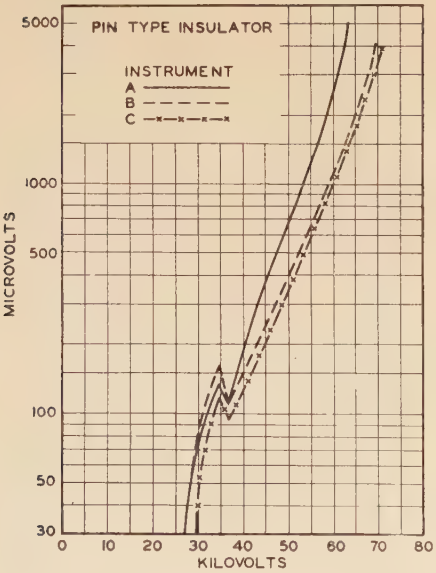

Figure 11. Comparison of radio-frequency voltages measured by three instruments (tests on insulator)

Relative air density = 1.0
Absolute humidity = 1 grain per cubic foot

Comparison of these two output meters was made by measuring the amplitude of the radio-frequency voltages produced by three devices. A signal generator was then connected to the input of the receiver and observers determined when the output of the signal generator and device under test indicated equal loudness.

The receiver used in these tests was the instrument *B*. This is, as stated above, a superheterodyne receiver. It employs one radio-frequency stage, oscillator, first detector, two intermediate amplifiers, second detector, and push-pull audio amplifier. A circuit analysis of it appears in *Radio*, November 1930. This receiver was equipped with a loud speaker. A Rectox output meter and the averaging tube voltmeter were connected in parallel and condenser coupled to the plates of the push-pull amplifier.

In making the measurements, the sensitivity of the receiver was adjusted so that the output of the noise was sufficient to give half scale deflection on the Rectox meter. The input potentiometer on the crest instrument (average tube voltmeter) was then adjusted so that maximum deflections could be read on the scale. A more exact determination of the pointer deflections was obtained by holding the edge of a card in front of the dial and adjusting it so that the needle was just visible for maximum variation. The adjustment of the input potentiometer was not changed during the time of test with any one observer. A signal generator with a 400-cycle audio component, and 50 per cent modulated output, was substituted for the noise source to determine the value of these two noise levels in microvolts.

The observer then compared by ear the relative volume obtained from the loud speaker when the noise source was connected to the receiver and when the signal generator output was substituted for the noise. The sensitivity of the receiver was held constant and the signal generator output adjusted until the two seemed to be of equal loudness.

The curves in figure 13 show the results of tests made with a 110-volt a-c universal-type motor, 33-kv pin-type insulator, and spark gap, respectively, as the source of the noise. The spark gap was used to produce a peak discharge which would simulate the type of noise from ignition systems.

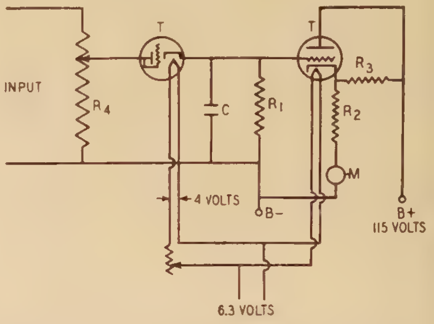

Figure 12. Circuit diagram of average tube voltmeter

R_1—40 megohms
R_2—68,000 ohms
R_3—680,000 ohms
R_4—500,000 ohms
C—0.007 microfarad
M—Rectifier-type meter
T—Tube type 76

It should be noted that the average tube voltmeter in all cases indicated higher values than the audio comparison. The present specified output meter indicated lower values by approximately the same amount. Present data indicate that the sensory build-up time, i.e., the time needed for a suddenly applied steady wave to build up to a steady loudness, is in the order of 0.2 to 0.25 seconds.[7] The average tube voltmeter will measure peaks of much shorter durations than the ear while the present output meter will only measure peaks of longer durations.

For practically all applications it appears that the present type of output meter gives an indication which is sufficiently close to the audio output of a radio receiver. This characteristic well justifies its use. It has the additional advantage of being simple and inexpensive which is highly desirable for industrial laboratory and field work.

Correlation Between Radio-Noise Measurement and Acoustical Loudness

The desirable radio noise measuring instrument is one that would indicate values which simulate the ear response. The American Standards Association has published tentative standards for acoustical noise measurement[8] and has formulated the requirements of sound level meters for measurement of noise and other sounds.[9] This instrument attempts to approach the human ear by weighing the various audio-frequency components with respect to the standard 1,000-cycle reference loudness level.

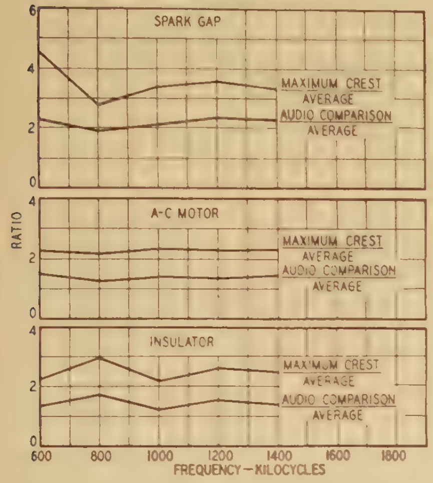

Figure 13. Comparison of audio, average, and crest values

It is interesting to note that the radio noise meter and the sound level meter primarily attempt to determine or weigh the effect of two different types of complex waves on the ear. One is used to measure the modulated high-frequency voltage while the other measures sound picked up by a microphone.

Tests were conducted to determine if any relationship existed between measuring the output of the radio set with Rectox-type output meter (instrument *B* in figures 10 and 11) and with a sound level meter which complies with the ASA standards.[10] The modulated radio-frequency voltages were produced by a rod-to-plate gap and measured by the standard radio noise method. In measuring the audio output of the radio set, the microphone of the sound level meter was placed at a distance of one foot directly in front of the loudspeaker. The scale of the output meter was zero to one. The volume control was adjusted for 0.1 on the output meter and the radio-frequency voltage and the sound level meter readings taken. The voltage on the rod gap was increased and for every 0.1 increase in deflection on the output meter, the modulated radio-frequency voltage and the sound level noise meter readings were noted.

Table II shows the results obtained with one sensitivity setting of the radio set. The radio-frequency voltages increased from 680 to 1,820 microvolts. The noise level increased from 75 to 90 decibels and the auditory sensation or loudness from 11,750 to 37,000 units. It should be noted that the microvolts increased 2.68 times and the auditory sensation 3.15.

Figure 14 shows three curves, each taken at a definite sensitivity and covering a given range of microvolts. In these three measurements the microvolts increased, respectively, 2.0, 7.0, and 4.0 times and the corresponding noise loudness increased 1.5, 5.5, and 5.2. These tests were made with the radio set at 1,000 kilocycles. Similar tests as for curve *C* but at 1,400 kilocycles gave a microvolt increase of 5.6 times against a loudness increase of 4.4 and at 600 kilocycles the microvolts increased 5.1 and the loudness 5.2.

Similar relationships in the relative increase between microvolts and loudness as shown in figure 14 were obtained with the microphone at greater distances from the loudspeaker. For instance, in one test similar to curve *C* but with the microphone placed at two feet directly in front of the loudspeaker, the microvolts increased 6.3 times while the loudness increased 6.0 times.

All these tests were made in one of the two laboratories where inherently the background noise level can readily be reduced to 50 decibels and even less so that it practically had no influence or required no compensation on the tests proper. An attempt was made to analyze the frequency components of the loudspeaker noise. It was found that the frequencies contained in this type of radio noise were too numerous and complex to permit frequency analysis.

From these tests the ratio of the increase in microvolts to the increase in auditory sensation did not vary more than 0.77 to 1.34. In a number of cases and on the average the ratio was close to one. If we assume that the response of the sound level meter simulates the human ear response, we can accordingly assume that our present output meter likewise corresponds in effect somewhat to the response of the human ear.

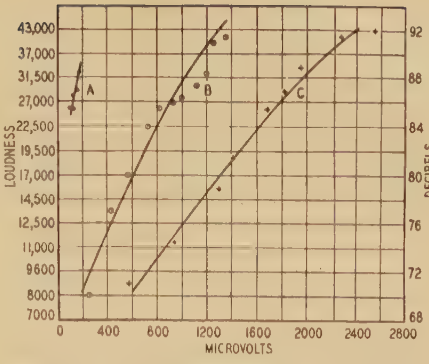

Figure 14. Correlation between radio noise measurements and acoustical loudness

Noise meter at 1,000 kilocycles
Volume dial setting *A*, *B*, *C*
Microphone one foot in front of loud-speaker
Radio-frequency voltage from three-inch rod to plate

Comparative Measurements of Corona Starting Voltage

Various means have been employed in determining the starting voltage of corona of high-voltage equipment. Recently tests were conducted to determine the effectiveness of detecting corona starting voltage by the use of a cathode ray oscilloscope, ear, eye, and the standard method of measuring radio noise.

Difficulty was encountered in attempting to use the cathode-ray oscilloscope and after considerable experimenting, an untuned radio-frequency choke coil was connected in series with the ground lead of the apparatus. A parallel resonant circuit tuned to 1,185 kilocycles was connected across this choke through a blocking condenser. The oscilloscope was then connected across this resonant circuit. By this means, the 60 cycle and low frequency harmonics were filtered out.

The tabulation below shows the threshold of corona by different methods from three pieces of apparatus. The standard method of measuring radio noise detected the lowest starting voltages.

In totally inclosed apparatus, the standard method of measuring radio noise detects corona starting voltage very much below the audible or visual methods.

	Kilovolts			
Sample	Audible	Oscillo-scope	Visual	Radio
High-voltage switch	26.0	28.2	26.0	20.0
Current transformer	11.0	12.0	12.0	6.2
Circuit breaker	6.1	7.7	13.0	4.85

Tests were made on the rod-to-plate (one-quarter-inch square rod) at various spacings. Initial audible corona was detected with an insulation tube of funnel-like shape which conveyed the sound at the rod end to the observer's ear. Corona could be detected by the ear at about 100 microvolts.

Comparative Tests in Air and in Oil

Electrical apparatus assumes many forms, depending on the application and on the design. It is apparent that a complete survey of the radio-noise influence of all apparatus would require an extensive program, although a good deal of work already has been done in this direction. However, an appraisal of this problem is simplified when it is recognized that most apparatus at the present operates either in air or in oil. The corona characteristics of these two dielectrics either alone or in combination with the dielectric bodies of the apparatus proper, such as porcelain, fullerboard, and so on, are important factors in a survey of the radio noise influence of electrical apparatus. Certain principles will become apparent from a consideration of typical tests which have been made in air and in oil.

Tests in air are shown in figure 15. These characteristic curves bear out in the first place the influence of the shape of the electrode. The radio noise measurements and therefore corona appear at a lower voltage when the electrode is a plain rod and it can be seen also that the characteristic curve is essentially the same whether this is a one-quarter-inch square rod or a one-eighth-by-one-inch rectangular strap. The curves show that for the same microvolt level twice the voltage may be applied to the sharp-cornered disk as compared to the voltage on the rod. A rounded electrode such as a sphere of sufficiently large diameter presents certain advantages in reducing corona formation, provided the surface of the electrode is kept clean. In practice apparatus may be exposed to dirt, moisture, rain, and so on, with the result that large smooth surfaces are in such case more detrimentally affected than would be the sharper-edged electrodes.

A point of interest in the characteristic curves for air (figure 15) is that considerably higher microvolt values are reached by the short gaps. Thus with the one-half-inch gap spacing, for either the rod or disk-type electrode, very high radio-frequency voltages can be generated whereas for the correspondingly larger gaps sparkover occurs before these high values can be reached.

In electrical apparatus the body of a solid dielectric or a combination of dielectrics appears between the line and ground electrodes assuming one form or another which depends on the design and the application of the apparatus. If the presence of the dielectric body increases or decreases the stress on the air as compared to the stress between the electrodes in air alone, then the microvolt-voltage characteristic curves will accordingly be modified, respectively, upward or downward. Thus the presence of the porcelain body in the case of the line insulator may further raise the microvolt-voltage curve in comparison to that of the tie wire and pin electrode in air alone. By proper design and grading of the body part, the stress on the air may be reduced. In the case of a condenser-type bushing the inherent grading of the stress in the dielectric body and over its surface contributes also in reducing the stress in the adjacent surrounding air. In this case the stress on the air at the line terminal even for sharp electrode parts is much less than it would be anticipated from the stress which appears between the terminal electrodes in air alone. It is apparent then that the radio-frequency voltage from electrical apparatus in air depends essentially on the relative stress imposed on the air. Characteristic curves of the air alone as shown in figure 15 are nevertheless of fundamental guidance in appraising the general problem.

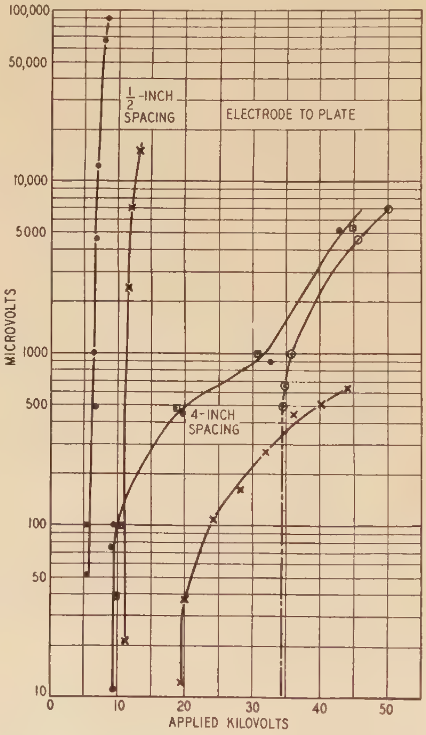

Figure 15. Radio-noise characteristics of air for various electrode arrangements

Type of electrode:
- ● One-quarter-inch square rod
- ⊡ One-eighth by one-inch rectangular strap
- × Nine-inch diameter, one-inch thick disk
- ⊙ 0.8-inch diameter sphere at end of one-half-inch diameter rod

The rod-to-plate gap was tested in oil at spacings from a fraction of an inch to an inch. The voltage was raised until breakdown of the oil gap occurred so that up to 45 kv was applied for the larger gap tested. No radio-frequency voltage could be detected up to breakdown of the gap.

Tests were made on fullerboard sheets in oil. The fullerboard was thoroughly dried out in a heating oven and oil impregnated under vacuum similar to the treatment for transformers. The sheets of fullerboard were immersed under oil in their own test tank. A sheet was pressed firmly between a $2^1/_2$-inch diameter disk with square edges and a grounded plate, as shown in figure 16 and tested. Curve *A* is the test result for a one-eighth-inch thick fullerboard and curves *B*, *C*, and *D* give similar tests for 0.056-inch fullerboard.

The characteristic curves *A*, *B*, *C*, and *D* rise abruptly and reach very high microvolt values. They clearly indicate that corona in oil is in effect much more intense than in air. In similar tests that had previously been made on the strength of insulation[11] the corona at the edge of the disk was detected visually at about 25 kv and 36 kv for the 0.056-inch and one-eighth inch fullerboard sheets, respectively. It appears to the writers that the radio noise method is also an effective means to study and measure corona. When the phenomena is partly or entirely concealed, such as is in these tests, it has been found a superior method to any of the others available. To illustrate this point further, a one-eighth inch fullerboard sheet that had not been dried or treated was tested. The results are plotted in curve *E* which by comparison to curve *A* show the benefits which accrue from drying and treating the fullerboard.

In practical design even for the lower classes of distribution apparatus, clearances in oil normally exceed the amount indicated in figure 16. The mechanical requirements alone generally require larger clearances. Besides the conducting parts normally are insulated thus securing relatively better performance than indicated. Considering the fact that the corresponding air clearances would be in the order indicated in figure 15, it is clearly apparent that the radio noise in-

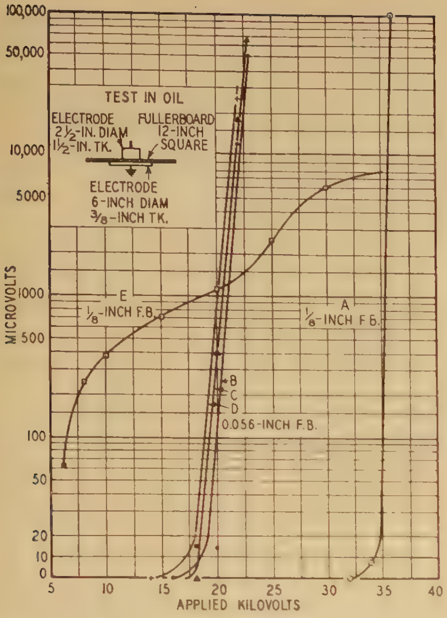

Figure 16. Radio-noise measurements of insulation in oil

fluence of electrical apparatus principally concerns the apparatus or the part of the apparatus in the air. Similar consideration of and experience with voltage apparatus of higher voltage classes likewise establish that normally only the apparatus in air need be tested for the effect of radio noise influence as the strength of the apparatus or corresponding part in oil well exceed in good design those in air.

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Discussion

C. W. Frick (General Electric Company, Schenectady, N. Y.): During the past six or seven years considerable experience has been gained with methods of determining radio influence characteristics of apparatus at several different laboratories and to some extent in field investigations. The present paper is a valuable contribution to this work. As the paper points out, the Joint Co-ordination Committee on Radio Reception of EEI, NEMA, and RMA has recommended circuits for the determination of interference influence of high-voltage and low-voltage apparatus. The quantity which is measured is called noise voltage in the committee report and is expressed in modulated microvolts, but in the paper it is called the radio influence factor. The name used in the paper has considerable merit because the quantity in question serves as an index of influence on radio reception. In this respect it is analogous to the telephone influence factor (TIF) which is a useful index of the influence of power-system wave shape on wire communication systems. On the other hand, the present name, noise voltage, has some advantage because it suggests the units in which the quantity is measured while a factor is generally thought of as a ratio, for instance power factor, form factor, space factor, and similar terms. The joint committee has not as yet adopted the name radio influence factor, and those wishing to use the term should explain its meaning as the authors have done.

The paper presents an interesting study of the effect of different types of output indicator. The present output meter is a microammeter which indicates an average of the rectified output of the radio receiver element of the noise meter. It is a critically damped instrument having an undamped period of 0.5 second as specified by the joint committee. Some engineers have suggested that an instrument which responds to noise peaks might give a better indication of the effects on radio reception. The paper compares the present output meter with one consisting of a tube voltmeter operated on a capacitance-resistance network characterized by rapid charge and slow discharge so that it tends to average the noise peaks. The authors call this an averaging tube voltmeter. Figure 13 of the paper shows that this averaging tube voltmeter gives higher readings than the present output meter for common types of noise, such as motor noise; that is, it requires a higher value of the calibrating voltage modulated 50 per cent to match the noise indication on that instrument than it does when the present output meter is used. This result would be expected because noises appear to consist of a rapid series of impulses. The curves also show that readings with the two instruments are different in ratios for different types of noise.

When the joint committee's specifications were prepared, it was realized that radio noise is quite complex and its effects on reception involve many factors including those associated with loud-speakers and with the ear. It was felt that the thing to do was to set up the best instrument that could be obtained according to the state of the art then, and to make improvements later as found necessary. Therefore they specify certain electrical characteristics for the receiver element and a certain period and damping for the output meter, based on the information then available. The paper includes an additional check on the present output meter by an ear comparison method where the noise is compared with the calibrating tone as heard in a loudspeaker. The curves of figure 13 for this audio comparison show better correlation with the present method than obtained by a similar test with the averaging tube voltmeter method. The present type of radio noise meter has been in the field for several years and has made it possible to collect useful data on common types of noise from different observers. For this purpose it seems to be better than anything else that has been suggested.

P. H. McAuley (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors have demonstrated the practical nature of the circuit recommended by the joint co-ordination committee. The radio influence factor of high-voltage apparatus can be checked in different laboratories at different times with different types of meter with good agreement. In addition to the East Pittsburgh laboratory described in the paper, which has been in operation since 1930, radio interference tests have been made at the Trafford laboratory from time to time. One of the 500-kv transformers is used, but the capacitor stack at present limits the voltage to about 200 kv. However, it is possible to test the highest voltage apparatus above its operating voltage to ground. At voltages above 150 kv, corona on leads and connections becomes somewhat of a problem. So far we have been able to use two-inch-diameter aluminum tubing with carefully made joints. Six-inch spheres are used at the ends. In general, a radio influence test, on 230 kv apparatus for instance, requires a careful arrangement of the complete high-voltage circuit.

For many years the laboratories have been able to make reliable tests. The crying need for years has been the establishment of levels of permissible noise for different classes of equipment. We are able to determine the radio influence characteristic curve of a piece of apparatus but we are unable to say whether it is satisfactory at its rated voltage. The establishment of levels is essentially an operating problem, because they should be based on experience with equipment now in service. It is hoped that it will soon be possible to correlate field and laboratory testing to the extent that permissible levels satisfactory to both manufacturer and user can be set.

A Position Regulator for Paper Slitters

By F. H. GULLIKSEN
MEMBER AIEE

PAPER slitters are used to trim the edges of paper webs so that a paper roll with even sides can be wound from an unevenly wound roll. When the paper has printed designs on it, the slitting must be done at a definite distance from the printed design. The slitter knives are stationary as shown in figure 1. In order to slit the paper at the same position relative to the design when the position of the paper relative to the shaft of the unwinding roll is varying, it becomes necessary to adjust the position of the unwinding roll transversely.

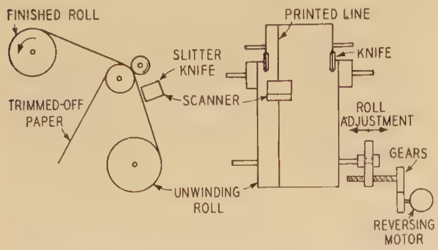

Figure 1. Schematic arrangement of paper slitter

To do this, a line is printed on the paper as part of the printed design and a phototube is arranged to scan this line. Through suitable electronic equipment and a reversing motor, the position of the unwinding roll is adjusted to keep the paper in the same position in relation to the slitter knives.

It has been customary to use a scanner with two phototubes which would scan the line printed on the paper as shown in figure 2. The phototubes were connected in a bridge circuit and the output of the bridge circuit was used to control the electronic regulator and the reversing motor.

The paper industry requires that the line printed on the paper should not be wider than one-eighth inch, which necessitates focusing the two light beams one-eighth inch apart, and obviously, the range of control with the scheme shown in figure 2 will be only one-eighth inch. If the paper, therefore, should move outside the one-eighth inch range, the regulator would lose control. It is also evident that any change in phototube or lamp characteristics would change the regulating position.

The purpose of this paper is to describe a new slitter regulator which employs only one phototube, and which widens the range of control to one inch regardless of the width of the printed line.

The Single Phototube Scanner

The new single phototube scanner shown in figure 3 consists of an 1,800-rpm synchronous motor with four lenses mounted on its shaft. A lamp is mounted as shown in figure 4 so that the lenses focus four light beams on the paper and the printed indicating line. A phototube is arranged to intercept the light reflected from the paper. A top view of the four lenses, the printed line, and the light beams L_1 to L_4, is shown in figure 5. In figure 5*A* the line is located in the center of the light-beam circle while in figure 5*B* the line is displaced to the left. The light beams rotate synchronously, each beam making one revolution in two cycles. Each time a light beam intercepts the line in the position indicated in figure 4, the illumination on the phototube is decreased. This change in phototube illumination is amplified as shown later in this paper, so that a peaked voltage impulse is obtained once every half cycle, referring to the frequency of the a-c source to which the synchronous motor is connected. The angular position of the lenses relative to the motor shaft is such that when the line is in position *A* the impulse voltage occurs at 90 degrees phase angle, whereas with the line in position 5*B* the impulse voltage location is advanced as shown in figure 6.

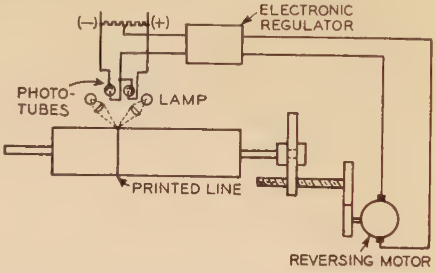

Figure 2. Slitter regulator employing two phototubes

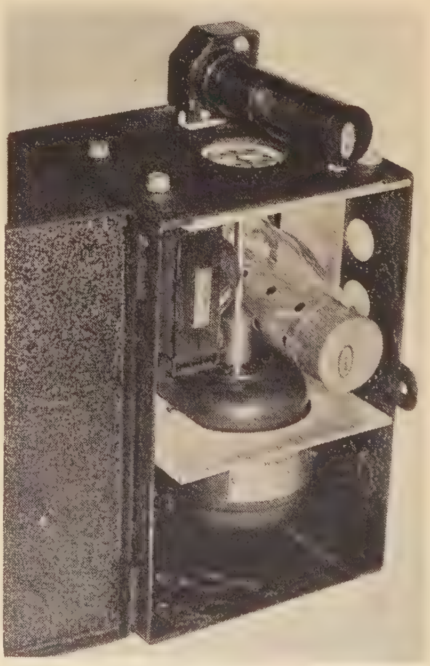

Figure 3. New scanner with one single phototube

For every position of the line on either side of the center position, an impulse is obtained, and there is a definite relationship between the angular location of the impulse voltage relative to the a-c supply voltage, and the space location of the line. This relationship is used to indicate the position of the paper.

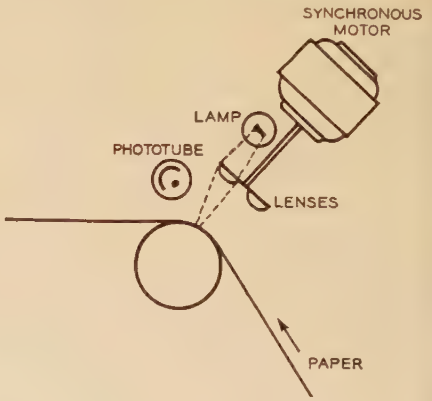

Figure 4. Schematic arrangement of single phototube scanner

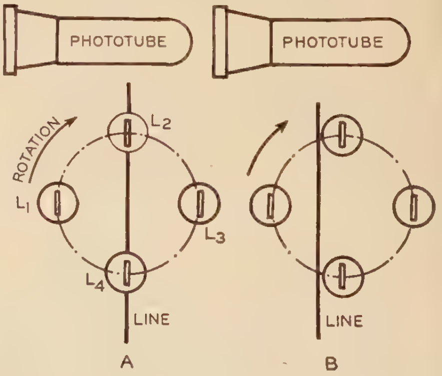

Figure 5. Development of light beams

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The Amplifier

A conventional amplifier with capacitor coupling in the grid circuit and transformer coupling in the anode circuit is used as shown in figure 9. The amplifier tube is normally biased to give a high anode current. When one light beam intercepts the line, and the illumination on the phototube is decreased, the grid of the amplifier tube is made highly negative and the anode current is decreased, thus giving an amplified impulse on the secondary side of the anode circuit transformer. This impulse is used to control the selective indicating circuit.

The Selective Indicating Circuit

The purpose of the indicating circuit is to detect the phase-angle location of the voltage impulse obtained from the amplifier. To make the circuit independent of variations in supply voltage and tube characteristics the circuit is arranged to respond only to phase angle. As shown in figure 7 two thyratron tubes 1 and 2 are used. The grid-control voltage for tube 2 is the amplified impulse voltage from the phototube, connected in series with a negative d-c bias voltage, and tube 2, therefore, is initiated at a point on the a-c voltage wave dependent upon the location of the impulse voltage E_i, which, as previously outlined, is a function of the space location of the line. When tube 2 becomes ionized, rectified a-c voltage appears across resistor 3, and persists during the remainder of the half cycle. The voltage across resistor 3 is connected in negative sense in the grid circuit of tube 1, so that tube 1 cannot become ionized if current is already established through resistor 3. Tube 1 has a permanent negative grid bias obtained from Rectox rectifier 5, which is supplied with a-c voltage from the 90 degrees phase-shift circuit consisting of resistor 6 and capacitor 7.

Because of the interlock action of resistor 3, tube 1 does not conduct current if the impulse voltage E_i occurs ahead of the 90 degrees position as shown in the curves in figure 7*B*. If the impulse voltage occurs later than the 90 degrees position current I_1 flows as indicated in figure 7*A*.

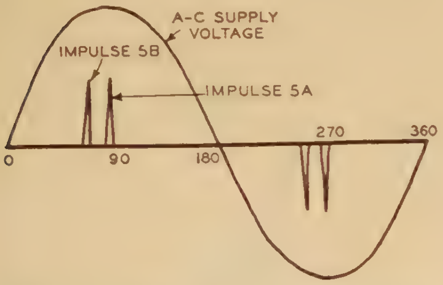

Figure 6. Location of the impulse voltage for positions 5A and 5B

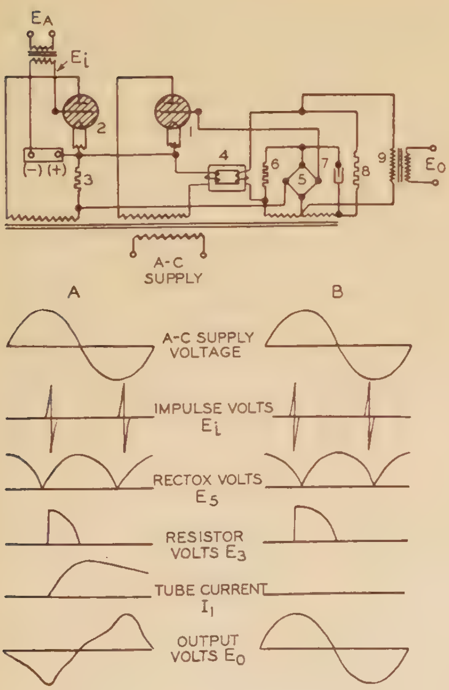

Figure 7. The selective indicating circuit

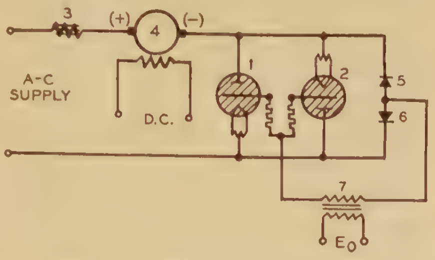

Figure 8. The motor-control circuit

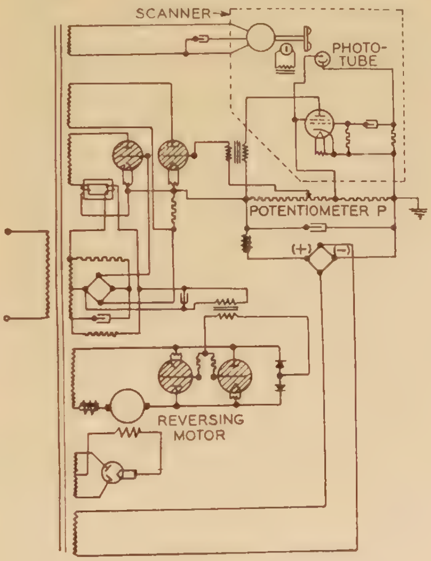

Figure 9. Schematic diagram for position regulator

Figure 10. A front view of the regulator cabinet

A saturable transformer 4 is connected in series with tube 1, and the secondary winding of this transformer is connected in a bridge circuit with resistor 8 so that the output voltage E_0 of transformer 9 is reversed when the primary winding of transformer 4 is energized. If, therefore, the line on the paper is moved from one side of the central position to the other, a 180 degrees reversal of voltage E_0 results. This condition is used to obtain reversal of the armature voltage for the roll-adjusting motor.

The Motor-Control Circuit

As shown in figure 8 two thyratron tubes 1 and 2 are used to supply reversiable rectified a-c voltage to the armature of the roll-adjusting motor. When tube 1 is conducting current the armature voltage polarity is as shown in figure 8. Reversal of armature polarity results when tube 2 is conducting. The current through tubes 1 and 2 is controlled by means of voltage E_0. Reversal of this voltage, in the manner previously described, reverses the grid polarity of the tubes so that one tube becomes ionized and current stops flowing in the other tube. Rectox rectifiers 5 and 6 are used to refer the grid voltage to the cathode of that tube whose anode at that instant is positive relative to the cathode.

Reactor 3 is used to limit the tube

A Static Constant-Current Circuit

By C. M. SUMMERS
ASSOCIATE AIEE

Synopsis: Static constant-current circuits have been constructed by connecting an iron-core reactor, with predetermined characteristics, in parallel with a capacitor of a specified size such that the resultant input current is independent of line voltage. This parallel circuit is connected in series with the element through which the current is to be regulated. The current will remain essentially constant for large variations in line voltage; large variations in load impedance; or a variation in both quantities simultaneously as long as the variation in voltage across the parallel circuit does not exceed certain limits. This type of circuit is useful for applications where a constant heating independent of line voltage is desired; for series lighting circuits; and vacuum-tube filament circuits.

AN IRON-CORE reactor and a capacitor, connected in parallel, are the essential elements of a static, a-c, constant-current circuit, providing these elements are operated within certain specified conditions. First, there must be a predetermined relation between the reactor and capacitor; second, the variation in voltage across this parallel circuit must be restricted to specified limits; and, third, the frequency must remain constant.

Theory of Constant-Current Circuit

Temporarily, assume that the reactor and capacitor in figure 1 are ideal units with their currents 180 degrees apart, and that both currents are sinusoidal. The volt-ampere curve of the capacity I_c, and of the reactor I_x, are plotted in figure 2 without regard to the phase relation between the two currents. The line current then I_0 is the numerical difference between I_c and I_x. Thus, at any value of voltage E_1 the line current is the horizontal distance between the two volt-ampere curves. It is evident, therefore, that the volt-ampere curve for the reactor must be parallel to that of the capacitor if the resultant current remains constant between the limits of voltage of E_1 and E_1'. If this condition exists for the circuit in figure 1, the current through the impedance Z will remain constant while either the line voltage or the series impedance varies; or while both vary simultaneously.

A reactor with a volt-ampere curve similar to that shown in figure 2 can be obtained by a bridge-gap iron core, one type of which is shown in figure 3. It consists of an air gap in parallel with a section of steel which can be saturated while a relatively low density exists in the remainder of the core. The length of the air gap controls the slope of the straight portion of the volt-ampere curve, while the saturated section governs the flux density, or voltage, at which the straight portion begins. This fact is illustrated in figure 4 by a series of volt-ampere curves derived from various physical dimensions of the saturated steel and the air gap. Great flexibility is obtained from this type of core because magnetic shims may be inserted in the air gap to adjust the volt-ampere curve to its desired position. Naturally, a rather high leakage flux surrounds the air gap and it is desirable, therefore, to place the air gap in such a location that the nonlinear characteristics of the reactor will not be altered by the proximity of other magnetic materials.

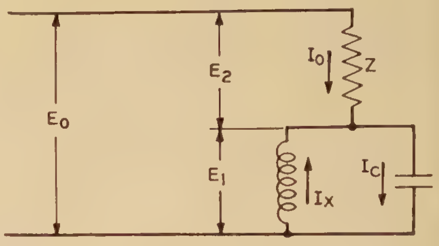

Figure 1. Parallel constant-current circuit

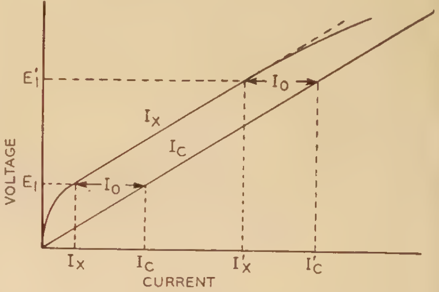

Figure 2. Current-regulating properties of nonlinear circuit

The core of the reactor should be made of low-loss steel to maintain as nearly as possible a 90-degree phase angle between the voltage E_1 and reactor current I_x. In practical designs, however, neither the reactor current nor the capacitor current are displaced exactly 90 degrees from the voltage. The line current is not, therefore, the algebraic difference between the two currents, but the vector sum of them. Thus, there are some fundamental relations in the parallel circuit which cannot be shown without a vector diagram indicating conditions for successive increments of voltage, as in figure 5. The locus of the resultant current is not exactly the arc of a circle, but it lies between the arcs of two circles which are quite close together. Suppose the vector terminating at G represents the resultant current in the line when the voltage E_1 is applied. Although the voltage may be increased as much as 100 per cent to E_1',

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peak current, particularly during the reversing period when the counter electromotive force of the motor armature reduces the effective resistance of the tube circuit. It was found that on account of the dynamic breaking action of the tubes during the reversing period, the circuit in figure 8 was particularly suited for this regulating application because idling and overtravel of the motor was practically eliminated, therefore producing very accurate and sensitive control.

Complete Schematic Diagram

Figure 9 shows the schematic diagram for the complete control circuit, and a photograph of the regulator is shown in figure 10. From figure 9 may be seen that only one single adjustment, potentiometer P, is used. The purpose of this potentiometer is to increase the sensitivity when the difference between the paper color and the line color is slight with reference to the color characteristic of the phototube. An example of colors of this characteristic is a red line on white paper. If the line color is black, blue, green or brown, the equipment will operate satisfactorily with any potentiometer adjustment, and because variations in tube characteristics do not affect the operation, the regulator will operate without any further adjustments after once being installed.

the vector of the resultant current will fall somewhere between the two circular arcs *CD* and *EF*. Beginning at the point *G*, the current increase in magnitude to the point *H*; then decreases in numerical value to the point *J*; and thereafter increases while the voltage over this range is continually increasing from E_1 to E_1'. The power factor is leading at all times but approaches unity as the voltage E_1 increases.

The Constant-Current Transformer

The simple nonlinear circuit described above is the heart of a constant-current transformer with no moving parts. To make a more complete circuit, a transformer which delivers load at unity power factor is inserted in series with the capacitor-reactor unit as shown diagrammatically by figure 6. The reactor has been converted into an autotransformer without affecting its reactance characteristics and the higher secondary voltage permits a more economical capacitor to be used on common 110-volt circuits. The vector diagram for the complete circuit is shown in figure 7 for only one value of line voltage. The resultant power factor is leading, but obviously it is more nearly unity than the power factor of the parallel branch of the circuit alone; that is, δ is less than α. The vector diagram in figure 8 shows the relation between the three voltages E_0, E_1, E_2 with a resistance load across the transformer for two values of line voltage.

The circuit shown in figure 6 will maintain a constant I_s in the load circuit for a variable line voltage, a variable load impedance or a variation of both providing the reactor and capacitor operate over a range of voltage through which the volt-ampere curves are parallel. With a constant resistance load it can be shown that the most economical design from the viewpoint of minimum capacity in microfarads occurs when the variation in voltage E_1 is $\sqrt{2}$ times the variation in line voltage. Also when the line voltage is constant and the resistance load variable the value of E_1' in figure 2 should be $\sqrt{2}$ times the value of E_1. (See also figure 9.) The load may operate at either lagging, or leading power factor, providing the limits of voltage E_1 are not exceeded.

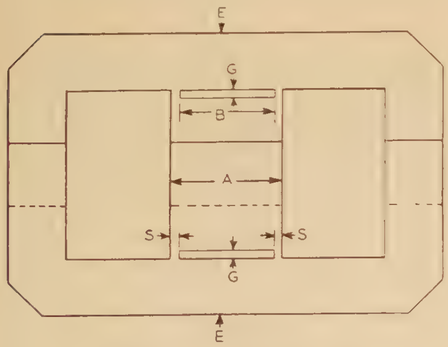

Figure 3. Bridge-gap core

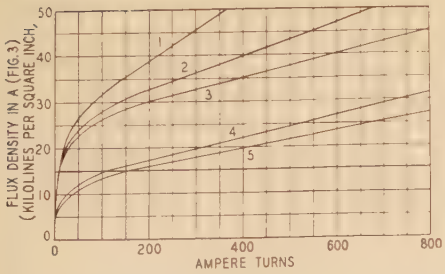

Figure 4. Calculated saturation curves for core shown in figure 3 (A = 1.375 inch)

Curve	*g* (Inch)	*s* (Inch)
(1)	0.062	0.125
(2)	0.125	0.125
(3)	0.187	0.125
(4)	0.187	0.062
(5)	0.25	0.062

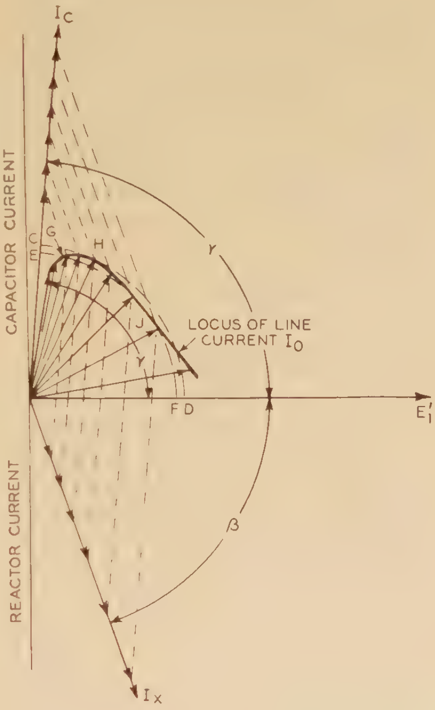

Figure 5. Successive vector diagram

Characteristics

The complete characteristics of a constant-current transformer supplying a resistance load are shown in figure 10. This unit was designed to operate on a line voltage varying between 105 and 125 volts and to deliver a constant current of one ampere at 25 volts. Between the specified limits of voltage, the output current actually varies from 1.04 amperes to 1.048 amperes.

The efficiency of the constant-current system varies between 50 per cent and 90 per cent. It is highest at the lowest value of line voltage and decreases in value as the line voltage increases. The power factor of the complete system is leading throughout the operating range for resistance load, and, like the efficiency, it is more nearly unity at the lower value of line voltage and decreases as the line voltage increases.

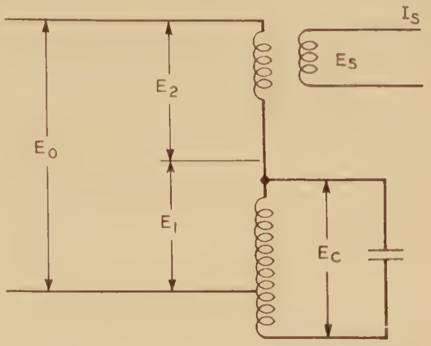

Figure 6. Constant-current-transformer circuit

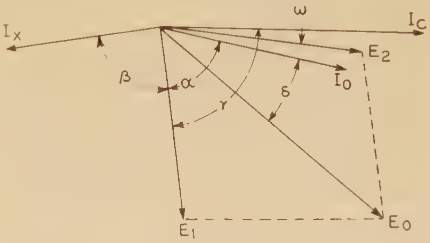

Figure 7. Vector diagram of constant-current transformer

Since reactance in the parallel circuit depends on frequency, it may be expected that the stable adjustment will be altered by changes in frequency and this is indeed the case. The volt-ampere curve of the reactor in figure 2 will swing toward the voltage axis as the frequency is increased, while that of the capacitor will swing toward the current axis as the frequency is increased. If a current-regulating circuit is designed to maintain a constant current at 60 cycles, it will gradually increase the line and load currents with increasing line voltage if the frequency is higher than 60 cycles. Conversely, if the frequency is less than 60 cycles the line and load currents will gradually decrease with increasing line voltages. Modern systems are so regulated that the variation in frequency may not exceed $^1/_8$ or $^1/_4$ of a cycle, and this is not great enough to injure the current regulating characteristics of a properly designed circuit. The characteristics of one current stabilizing unit on 59, 60, and 61 cycles are illustrated in figure 11.

Generally speaking, this particular type of nonlinear circuit has many interesting characteristics depending on the relation between the capacitor and reactor volt-ampere curves. Suppose, for example, the two curves in figure 2 intersect. The line current will contain a maximum value corresponding to the maximum horizontal distance between the two curves, and it will approach zero at the intersection. An unlimited number of characteristic curves of line voltage plotted against line current can be obtained, some of which are useful for current- and power-limiting circuits. A phenomenon of instability is encountered when certain relations exist between the series and parallel components of the circuit, but a discussion of this phenomenon is beyond the scope of this paper.

A nonlinear circuit designed to deliver a constant current when applied to a sinusoidal line voltage will not necessarily maintain a constant current when applied to voltage with other wave forms, because a distorted wave will produce approximately the same results as an increase in frequency. By properly adjusting the reactor, however, a constant-current transformer may be made to operate on distorted voltage with reasonable satisfaction. Inherently, the current stabilizing system does not produce a badly distorted wave as indicated by the oscillogram of load and current in figure 12. The reactor and capacitor currents each contain a large third harmonic but their phase relation is such that they circulate around the parallel circuit and thereby are greatly restricted from flowing in the line. Transients existing in the line voltage will disturb the regulation in the load circuit, to a certain extent as indicated in figure 13. The oscillogram shows the line voltage and output voltage on the current stabilizer when the line voltage is rapidly changed from its minimum to maximum value, which in this case was from 85 to 125 volts.

The static constant-current circuit has been applied to numerous filament-control circuits for maintaining a constant filament current on variable-voltage circuits. When the load is constant, of course, the same circuit will maintain a constant load voltage. The permissible variation in line voltage depends upon the design of the reactor and in some instances a constant current (plus or minus two per cent) has been maintained over a 500 per cent variation in line voltage. This requires a rather extreme and bulky design. For lines having a total voltage variation of 50 per cent the static constant transformer is from twice to three times the physical size of an ordinary transformer with the same rating.

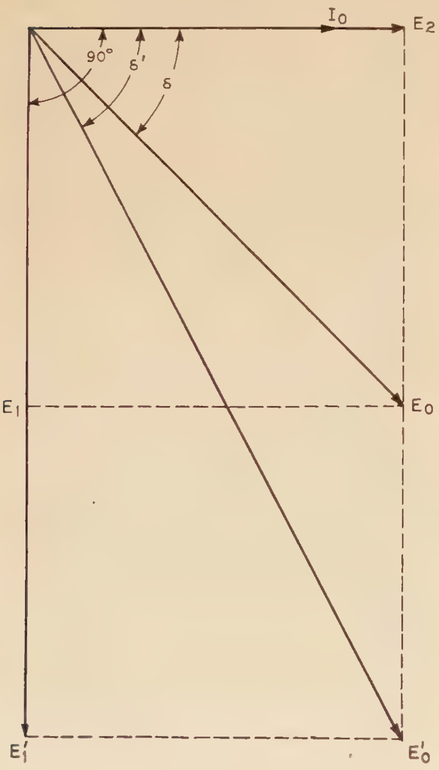

Figure 8. Vector diagram of ideal constant-current transformer for two values of line voltage

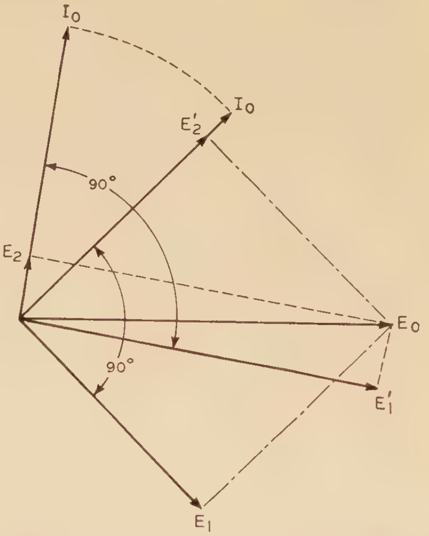

Figure 9. Vector diagram of constant-current transformer with constant line voltage and a variable resistance load

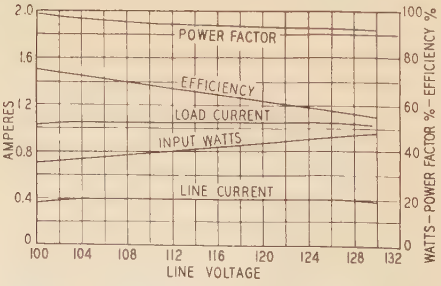

Figure 10. Characteristic curves of a 25-watt constant-current transformer

Appendix

Derivation of Formulas for Variable Line Voltage

A mathematical derivation of design formulas for a nonlinear circuit to operate on a variable line voltage and to maintain a constant current in a fixed, resistance load is given below. Sinusoidal currents and voltages are assumed and the losses in the reactor and capacitor are neglected. In all cases symbols without primes are minimum values and those with primes are maximum values.

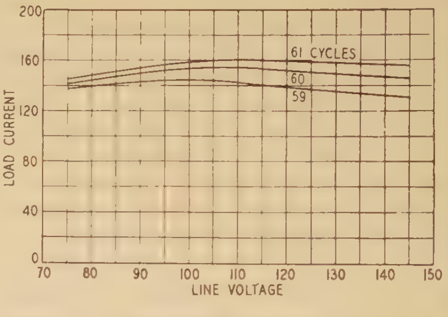

Figure 11. Frequency-regulation for a 150-watt, one-volt constant-current transformer

The circuit diagram in figure 6 and the vector diagram in figure 8 apply. From figure 8 the fundamental equations are:

$$E_1^2 + E_2^2 = E_0^2 \tag{1}$$

and

$$(E_1^1)^2 + E_2^2 = (E_0^1)^2 \tag{2}$$

Subtracting (1) from (2), we have

$$(E_1^1)^2 - E_1^2 = (E_0^1)^2 - E_0^2 \tag{3}$$

Let k represent the ratio between the maximum and minimum values of voltage across the reactor-capacitor unit. That is,

$$E_1^1 = kE_1 \tag{4}$$

Also let d represent the ratio between the maximum and minimum values of line voltage. Thus,

$$E_0^1 = dE_0 \tag{5}$$

Substituting (4) and (5) in (3) for E_1^1 and E_0^1, respectively, and solving for E_1 we get,

$$E_1 = E_0\sqrt{\frac{d^2 - 1}{k^2 - 1}} \tag{6}$$

From equation (1),

$$E_2 = \sqrt{E_0^2 - E_1^2} \tag{7}$$

Substituting (6) in (7), we obtain

$$E_2 = E_0\sqrt{\frac{k^2 - d^2}{k^2 - 1}} \tag{8}$$

The capacitor must have the highest volt-ampere rating of any element in the circuit. The current passing through it is the sum of the exciting current and load current. It is desirable, therefore, to keep the size of capacitor at a minimum, by properly adjusting k with respect to d.

The volt-ampere rating (M) of the capacitor is independent of the voltage to which it is referred. That is, from figure 6,

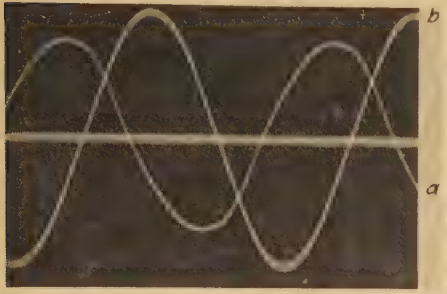

Figure 12. Wave form of load current of a constant-current transformer

a—Load current b—Line voltage

$$M = E_1I_c \tag{9}$$

Where the current is referred to the low voltage side of the autotransformer.

Allowing I_c/I_0 (see figure 2) to be represented by the symbol P equation (9) becomes

$$M = E_1PI_0 \tag{10}$$

The value P has a physical significance in that it represents the degree of current utilization. The capacitor is capable of supplying the current I_c in the line, but of this quantity I_x is taken to excite the nonlinear reactor which leaves I_0 available for output. The value of P is a constant for any core and depends on the sharpness of the knee, and the slope of linear portion of the saturation curve. It applies only at the minimum value considered.

The line current required (see figure 6) is

$$I_0 = \frac{W}{E_2e} \tag{11}$$

where

W = load watts

e = efficiency of output transformer

Then substitute (11) in (10)

$$M = \frac{E_1PW}{E_2e} \tag{12}$$

and again substituting (6) and (8) in (12) we have

$$M = \frac{PW\sqrt{d^2 - 1}}{e\sqrt{k^2 - d^2}} \tag{13}$$

Since $I_c = 2\pi fCE_1 \times 10^{-6}$ the capacity required in microfarads is

$$C = \frac{M}{2\pi fE_1^2} \times 10^6 \tag{14}$$

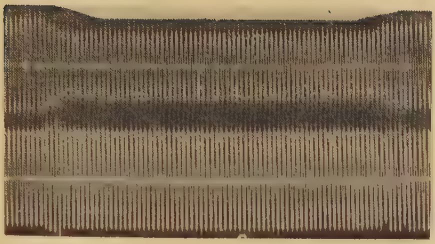

Figure 13. Effect of transients in constant-current transformer when the line voltage is rapidly changed (125 to 85 to 125 volts)

Above—Line voltage Below—Load voltage

Substituting (13) for the value of M in (14),

$$C = \frac{PW\sqrt{d^2 - 1}}{2\pi fE_1^2e\sqrt{k^2 - d^2}} \times 10^6 \text{ microfarads} \tag{15}$$

Equation (15) indicates the size of the capacitor necessary if placed directly across the voltage E_1. If the capacitor is placed across the secondary of the autotransformer as in figure 6, it is necessary to replace E_1^2 by E_c^2. The maximum voltage that can be impressed safely on the capacitor is a limiting feature of the design and it must be incorporated in the design formulas. If we let E_c^1 be this maximum voltage allowable, then E_1^2 in equation (15) should be replaced by E_c^1/k. Equation (15), with this transformation, becomes

$$C = \frac{PW\,k^2\sqrt{d^2 - 1}}{2\pi f(E_c^1)^2\,e\sqrt{k^2 - d^2}} \times 10^6 \text{ microfarads} \tag{16}$$

Equations (6), (8), and (16) are general equations representing the voltage across the reactor-capacitor unit, the voltage across the primary of the transformer, and the capacity required in parallel with the reactor or autotransformer. These general equations are derived in terms of known constants, the variation in voltage existing on the line, and the variation in voltage across the parallel branch of the circuit. There are a number of values for the constant k and an equal number of sizes of capacitor which will meet all of the requirements for maintaining a constant current. When equation (16) is differentiated with respect to k, the value of k corresponding to the minimum value of capacitor can be obtained. Before the equation is differentiated, however, it can be reduced to a more simple form. For any specific design, all quantities in (16) are constant except k; and all fixed terms except d can be included in a constant term Q. Thus,

$$C = \frac{k^2Q\sqrt{d^2 - 1}}{\sqrt{k^2 - d^2}}$$

or

$$\left(\frac{C}{Q}\right)^2 = \frac{k^4(d^2 - 1)}{k^2 - d^2} = y \tag{17}$$

When y is a minimum, C must also be a minimum; therefore, y can be differentiated with respect to k.

We find thereby that C is minimum when

$$k = \sqrt{2}\,d \tag{18}$$

Substituting this value of k in equations (6), (8), and (16), respectively, we obtain the design equations for the most economical conditions.

$$E_1 = E_0\sqrt{\frac{d^2 - 1}{2d^2 - 1}} \tag{19}$$

$$E_2 = E_0\sqrt{\frac{d^2}{2d^2 - 1}} \tag{20}$$

$$C = \frac{WPd\sqrt{d^2 - 1}}{(E_c^1)^2\pi fe} \times 10^6 \text{ microfarads} \tag{21}$$

Derivation of Formulas for Constant Line Voltage

The derivation of design formulas for a current-regulating circuit operating on a constant line voltage to supply a variable resistance load with a constant current is given below. The same assumption and nomenclature previously established apply to this circuit. The circuit diagram in figure 6 applies, but the vector diagram is shown in figure 9. The important difference between this circuit and the one previously analyzed is that the maximum value of reactor voltage, E_1^1, exists simultaneously with the minimum value of output transformer voltage, E_2, and vice versa. The symbol m is defined as

$$m = E_2^1/E_2$$

A procedure similar to that outlined above produces equations for minimum capacitance as follows:

$$k = \sqrt{2} \tag{22}$$

$$E_2 = E_0\sqrt{\frac{1}{2m^2 - 1}} \tag{23}$$

$$E_1^1 = E_0\sqrt{\frac{2(m^2 - 1)}{2m^2 - 1}} \tag{24}$$

and

$$C = \frac{I_0E_0P\sqrt{m^2 - 1}}{\pi f(E_c^1)^2\sqrt{2m^2 - 1}} \times 10^6 \text{ microfarads} \tag{25}$$

The above equations are sufficient to completely design a constant-current circuit with the exception of one factor; namely, the number of turns on the primary of the nonlinear reactor. The saturation curve for the core with flux density plotted against ampere-turns, of course, must be available; and a parallel line representing the capacitor volt-amperes must be drawn to the straight portion of the saturation curve. The horizontal distance between the two lines will represent ampere-turns and will correspond to the value in figure 2. The required line current I_0 can be determined easily for the design from the load requirement. If NI represents the horizontal distance between the saturation curve and the capacitor line in ampere-turns, and T represents the number of turns on the primary of the nonlinear reactor or autotransformer, the following equation applies:

$$T = \frac{NI}{I_0} \text{ (from curve)} \tag{26}$$

Analysis and Design of Harmonic Generators

By FREDERICK EMMONS TERMAN
MEMBER AIEE

HARMONIC generators such as used in radio transmitters are usually designed and adjusted on the basis of experience because the only analysis of their performance that has been available is a laborious point-by-point method of attack which is much too cumbersome to be practical in the general run of problems. In the present paper a new method of analyzing the harmonic generator is presented that involves a minimum of labor and at the same time has an accuracy entirely adequate for design purposes.

Voltage and Current Relations in Harmonic Generators

The circuit of a typical harmonic generator is shown in figure 1*a*, and is similar to a class-*C* amplifier circuit except for the fact that the plate tank circuit is tuned to a harmonic of the exciting voltage. When properly adjusted the instantaneous voltages, currents, and powers follow oscillograms such as indicated in figure 1. (The assumption of a sinusoidal alternating plate voltage in figure 1 is equivalent to saying that the Q of the plate tank circuit is high enough to make the voltage drop across it negligible for all alternating components except the desired harmonic.) The grid bias is made considerably greater than cutoff and sufficient signal voltage is applied to drive the grid somewhat positive. The result is that the space current flows in pulses having a relatively large peak amplitude but lasting for only a small fraction of the cycle. Such pulses have a large harmonic content, and the tank-circuit impedance is adjusted so that the desired component builds up a crest voltage across this circuit that is only slightly less than the plate-supply potential. This makes the minimum plate potential reached during the cycle quite small, as shown. The instantaneous power supplied to the plate circuit of the harmonic generator is equal to the plate-supply potential multiplied by the instantaneous plate current, as shown in figure 1*g*. This power is divided between loss at the plate of the tube and useful output delivered to the tank circuit in proportion to the instantaneous voltage drops existing across these parts of the circuit. Similarly the power loss at the grid at any instant equals the instantaneous grid current times the instantaneous grid-cathode potential, and the power that the grid exciting voltage must supply is likewise equal at any instant to the product of grid current and exciting voltage at that moment.

Simplified Analysis of Harmonic Generators

The oscillograms of figure 1 provide a means for making an exact analysis of the performance of the harmonic generator. These oscillograms can be drawn from the characteristic curves of the tube for any assumed voltages acting on the grid and plate electrodes. The practical usefulness of the result is, however, limited by the large amount of work required to plot the various curves point by point and to planimeter them to get averages.

An approximate analysis can be made by noting that the pulses of total space current in figure 1 appear upon inspection to approximate a section of a sine-wave pulse raised to some power of the order of 3/2. In screen-grid and pentode tubes, and in high-mu triodes, the space-current pulses are in fact almost exactly sections of such a sine pulse because of the fact that in these cases the plate voltage has little or no effect upon the total space current, which is then determined by a sine wave driving voltage of fundamental frequency. The analysis of harmonic generators under such conditions has already been outlined in earlier papers,[1,2] and makes use of curves giving the ratio I_0/I_m of average current to peak space current, and the ratio I_n/I_m of harmonic component of the space current pulse to peak value of pulse, in terms of the number of electrical degrees θ during which the space current flows. Such curves are given in figure 2.

In the case of harmonic generators employing ordinary triode tubes the space-current pulse does not have a shape that is exactly a section of a sine wave raised to some power. This is because the effective voltage producing the current pulse is a combination of fundamental-frequency and harmonic voltages, which obviously cannot follow exactly a section of a simple sine wave. The extent of the discrepancy depends upon the angle of current flow, the tube characteristics, etc. A practical procedure for analyzing the ordinary triode harmonic generator can, however, be worked out by assuming as a first approximation that the space-current pulse follows a section of a simple sine wave raised to a power, and then applying a correction to this result in order to take into account the discrepancy between the assumed and actual pulse shape.

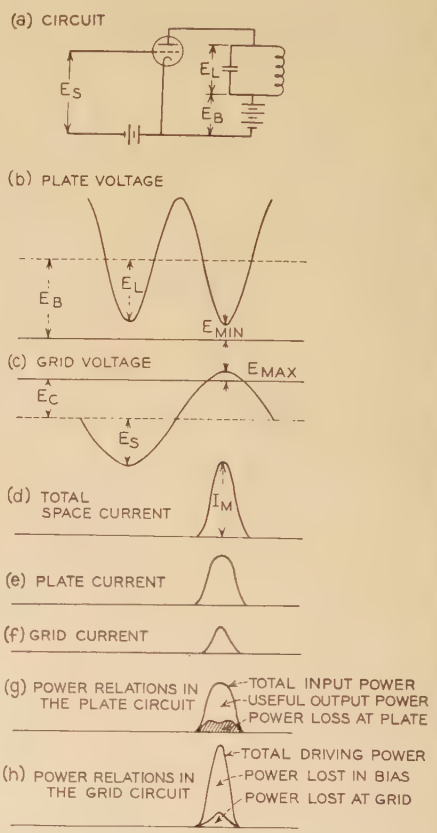

Figure 1. Circuit of typical harmonic generator, together with voltage, current, and power oscillograms

Curves giving the correction factor that must be applied to results obtained on the sine-wave section assumption are given in figure 3 for linear and square-law tube characteristics. The derivation of these curves follows.

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1. For all numbered references, see list at end of paper.

Mathematical Analysis

NOTATION

e_1 = net voltage available to produce electrostatic field in the vicinity of the cathode for the case of simple sine-wave pulse

e_h = net voltage available to produce electrostatic field in the vicinity of the cathode for harmonic generator case

$E_{\max}$ = $E_s - E_c$ = maximum instantaneous grid potential reached during cycle (see figure 1)

$E_{\min}$ = $E_B - E_L$ = minimum instantaneous plate potential reached during cycle (see figure 1)

θ = number of electrical degrees during which current flows (see figure 1) (based on fundamental frequency)

E_s = crest signal voltage (see figure 1)

E_L = $E_B - E_{\min}$ = crest alternating voltage developed between plate and cathode (see figure 1)

E_c = grid bias

E_B = d-c plate-supply potential

μ = amplification factor of tube

n = harmonic involved

E_m = $E_{\max} + \dfrac{E_{\min}}{\mu}$ = crest amplitude of e_1 or e_h

k = $(E_L/\mu)/E_m$

$A = 1 - \cos\theta/2$

$B = 1 - \cos n\theta/2$

$C = \dfrac{B-A}{A} = \dfrac{\cos\theta/2 - \cos n\theta/2}{1-\cos\theta/2}$

The net effective voltage available to produce a space-current pulse when the signal voltage and the output voltage are of the *same* frequency (class-*C* amplifier action), is

$$e_1 = \left(E_s - \frac{E_L}{\mu}\right)\cos\omega t - E_c + \frac{E_B}{\mu} \qquad (1)$$

$$= E_m\frac{(\cos\omega t - \cos\theta/2)}{1-\cos\theta/2} \qquad (1a)$$

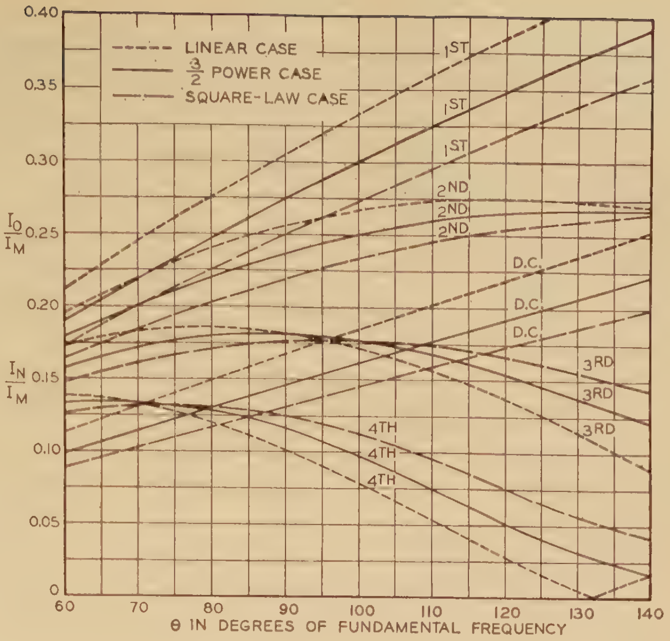
This voltage produces a space current that for positive e_1 is very nearly proportional to e_1^{α}, where α lies between one and two and is normally very close to 3/2. The space current is assumed to be zero when e_1 is negative.

The net effective voltage producing electrostatic field at the surface of the cathode when the alternating plate voltage E_L is a *harmonic* of the exciting voltage is

$$e_h = E_s\cos\omega t - \frac{E_L}{\mu}\cos n\omega t - E_c + \frac{E_B}{\mu} \qquad (2)$$

A comparison of equations (1) and (2) shows that e_h fails to be a section of a simple sine wave exactly to the extent that the term $(E_L/\mu)\cos n\omega t$ fails to follow a sine-wave section of fundamental frequency in the interval $\omega t = -\theta/2$ to $\omega t = \theta/2$, (i. e., the interval *abc* in figure 4). The error involved in using the curves of figure 2 to give the space-current pulses is then caused by the discrepancy between the dotted and solid curves in figure 4, where the dotted curve corresponds to a wave of fundamental frequency coinciding with the actual harmonic curve at points *a*, *b*, and *c*.

Figure 2. Curves giving the d-c and harmonic components of space-current pulses that are produced by an effective driving voltage that is a section of a simple sine wave



The magnitude of this error can be evaluated by taking the difference of the dotted and solid curves in figure 4. The equation of the solid (harmonic) curve in figure 4 is

$$e' = \frac{E_L}{\mu}\cos n\omega t \qquad (3)$$

while the equation of the dotted (fundamental) curve referred to the same axis is

$$e'' = \left(\frac{E_L}{\mu} + \beta\right)\cos\omega t - \beta \qquad (4)$$

where β represents the axis of the dotted curve as shown in the figure, and the two curves are assumed to coincide at *b*. The value of β is determined by the fact that the dotted curves must also pass through points *a* and *c*. That is

$$\frac{E_L}{\mu}\cos n\theta/2 = \left(\frac{E_L}{\mu} + \beta\right)\cos\theta/2 - \beta \qquad (5)$$

Eliminating β in (4) by means of (5) gives

$$e'' = \frac{E_L}{\mu}\left\{\left(\frac{1-\cos n\theta/2}{1-\cos\theta/2}\right)\cos\omega t - \frac{\cos\theta/2 - \cos n\theta/2}{1-\cos\theta/2}\right\} \qquad (6)$$

$$= kE_m\left\{\frac{B}{A}\cos\omega t - C\right\} \qquad (7)$$

where k, E_m, A, B, and C are as defined in the table of notation.

The difference $e' - e''$ then gives the error in the net effective voltage available to produce space current that results by assuming that the effective voltage producing the space current pulses is a section of a simple sine wave. This difference is

$$D = kE_m\left\{\cos n\omega t - \frac{B}{A}\cos\omega t + C\right\} \qquad (8)$$

Here D is the amount by which the actual shape of the pulse for the case of nth harmonic generation is *less* (note negative sign of E_L in equation 2) than the effective voltage that would be acting if the pulse was determined by a simple sine-wave section of same θ and same maximum value. As a consequence, the difference term D given by equation (8) must be *subtracted* from the pulse obtained on the assumption of a sine-wave section in order to obtain the true amplitude.

In the case of a tube having a linear characteristic, the space current is proportional to the equivalent voltage producing electrostatic field in the vicinity of the cathode. Hence the error in the average or d-c component of the total space current made by assuming a section of a simple sine wave is equal to the average of D in equation (8) over the interval θ. Assuming for convenience that $E_m = 1$, then the average D_0 of D is

$$D_0 = \frac{1}{2\pi}\int_{-\theta/2}^{\theta/2} D\, d(\omega t)$$

$$= \frac{k}{\pi}\left\{\frac{\sin n\theta/2}{n} - \frac{B}{A}\sin\frac{\theta}{2} + C\frac{\theta}{2}\right\} \qquad (9)$$

The average of equation (1) as a function of the angle of flow θ has been previously derived, and is given in figure 2. The ratio of D_0 to the average of equation (1) then gives the fractional error that must be subtracted from the average or d-c space current obtained from figure 2 in order to correct for the fact that the space-current pulse is not exactly a section of a simple sine wave. Values of this fractional error are given by the dotted curves in figure 3 for the case where the constant k is unity. The fractional errors for other values of k will be directly proportional to k.

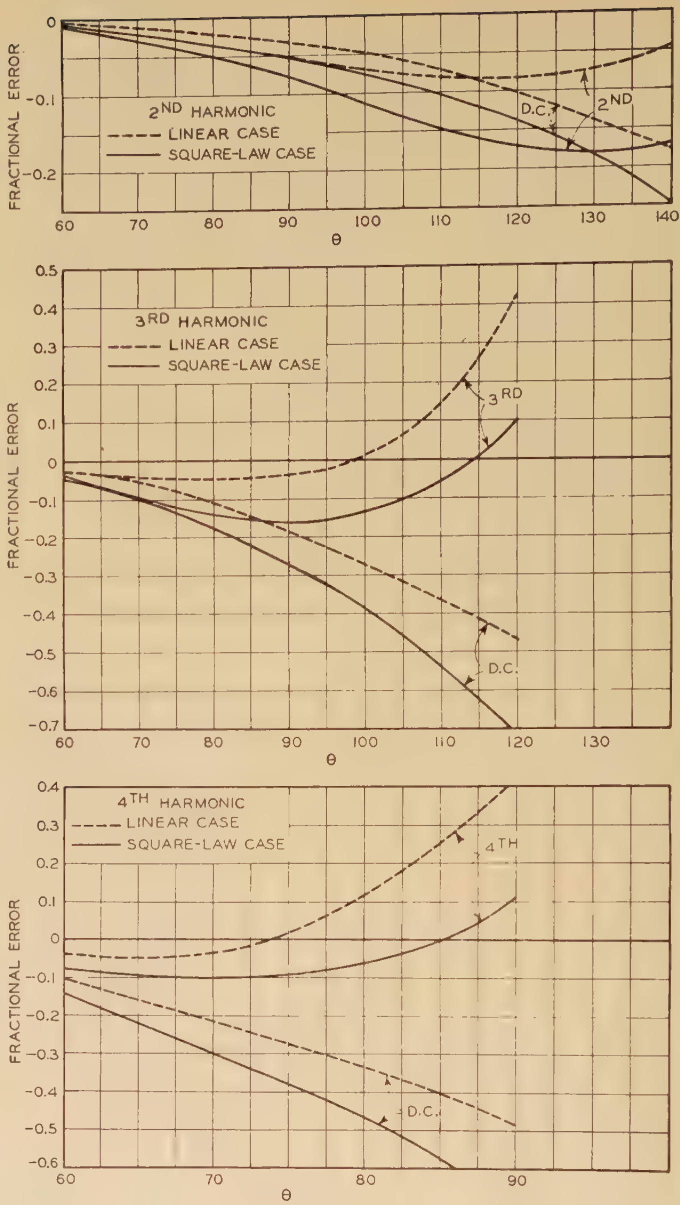


Figure 3. Curves giving the fractional corrections that must be subtracted from results obtained from figure 2 to obtain correct results for harmonic-generator action. These curves assume k = 1. The correction for other values of k is proportional to k

The error D_n in the nth-harmonic component of the space current for the linear case, assuming E_m unity, is given by

$$D_n = \frac{1}{\pi}\int_{-\theta/2}^{\theta/2} D \cos n\omega t \, d(\omega t)$$

$$= \frac{2k}{\pi}\left\{\frac{1}{4n}(n\theta + \sin n\theta) - \frac{B}{A}\left(\frac{\sin (n-1)\theta/2}{2(n-1)} + \frac{\sin (n+1)\,\theta/2}{2(n+1)}\right) + \frac{C}{n}\sin\frac{n\theta}{2}\right\} \quad (10)$$

The fractional error that must be subtracted from the value of nth harmonic obtained from figure 2 on the assumption of a sine-wave pulse is then the result obtained from equation (10) divided by the nth-harmonic component of the space-current pulse on the assumption of a simple sine-wave section as obtained from figure 2. Values of this ratio are given by the dotted lines of figure 3.

Consider next the case where the total space current is proportional to the square of the effective voltage producing electrostatic field near the cathode. The true value of space-current pulse is then proportional to $(e_1 - D)^2 = e_1^2 - 2e_1D + D^2$. The error involved in assuming that the pulse has a shape based upon a section of a sine wave is obviously $2e_1D + D^2$. However if the error D is not large compared with e_1, as is the case under practical conditions, then D^2 can be neglected and the error becomes very nearly $2e_1D$. The error D_0' in the average or d-c component of the total space current is hence (assuming E_m is unity)

$$D_0' = \frac{1}{2\pi}\int_{-\theta/2}^{\theta/2} 2e_1 D$$

$$= \frac{1}{\pi}\int_{-\theta/2}^{\theta/2} \frac{\cos\omega t - \cos\theta/2}{1 - \cos\theta/2} D d(\omega t)$$

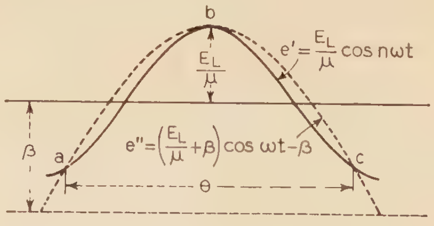
$$= \frac{2k}{\pi A}\left\{\frac{\sin (n-1)\,\theta/2}{2\,(n-1)} + \frac{\sin (n+1)\theta/2}{2\,(n+1)} - \frac{B}{4A}(\theta + \sin\theta) + C\sin\theta/2\right\} - \frac{2D_0\cos\theta/2}{A} \quad (11)$$

The ratio of this to the d-c value obtained from figure 2 for a square-law characteristic is then the fractional error involved in assuming that the pulses in the harmonic generator are based on the square of a section of a simple sine wave. Values for this fractional error are given by the solid lines in figure 3. In a similar manner the error D_n' in the nth harmonic component of the total space current that is involved in assuming that the pulse is the square of a section of a simple sine wave is

$$D_n' = \frac{1}{\pi}\int_{-\theta/2}^{\theta/2} 2e'D\cos n\omega t \, d(\omega t)$$

$$= \frac{2}{\pi}\int_{-\theta/2}^{\theta/2} \frac{\cos\omega t - \cos\theta/2}{1 - \cos\theta/2} D \times \cos n\omega t \, d(\omega t)$$

$$= \frac{2k}{\pi A}\left\{\sin\frac{\theta}{2} + \frac{\sin (2n-1)\,\theta/2}{2\,(2n-1)} + \frac{\sin (2n+1)\,\theta/2}{2\,(2n+1)} - \frac{B}{A}\left[\frac{\sin n\theta/2}{n} + \frac{\sin (n-2)\,\theta/2}{2\,(n-2)} + \frac{\sin (n+2)\,\theta/2}{2\,(n+2)}\right] + C\left[\frac{\sin (n-1)\theta/2}{(n-1)} + \frac{\sin (n+1)\theta/2}{(n+1)}\right]\right\} - \frac{2\cos\theta/2}{1 - \cos\theta/2} D_n \quad (12)$$



b
$e' = \frac{E_L}{\mu}\cos n\omega t$
$\frac{E_L}{\mu}$
$e'' = \left(\frac{E_L}{\mu} + \beta\right)\cos\omega t - \beta$
β
a
c
θ

Figure 4. Approximation of a section of a sine-wave section of harmonic frequency by a section of a sine wave of fundamental frequency

The ratio of the error given by equation (12) to the nth-harmonic component of the space current for the square-law characteristic as given in figure 2 is then the fractional error. This is plotted in figure 3 for various harmonics as a function of angle of current flow.

Calculation of Harmonic-Generator Performance

It is now possible to calculate the performance of the harmonic generator for any given set of operating conditions. In doing this the operating condition is defined in terms of the angle of current flow θ, maximum grid potential $E_{\max}$, minimum plate potential $E_{\min}$, grid bias, and plate-supply voltage. The first step is to determine the peak total space current I_m and peak grid current I_{gm} corresponding to the given values of $E_{\max}$ and $E_{\min}$, by using characteristic curves as supplied by the tube manufacturer. The d-c and harmonic components I_0 and I_n of the total space current for this value of I_m are then obtained from figure 2, assuming that the current pulse is a section of a sine wave raised to a power of the order of 3/2. The next step is to determine from figure 3 the fractional corrections for the d-c and harmonic components, interpolating between the dotted and solid curves according to the exponent used in connection with figure 2. These fractional corrections are then multiplied by the value of k for the case at hand, and the necessary corrections determined, and subtracted from the results of figure 2 to give the components of the actual pulse of total space current.

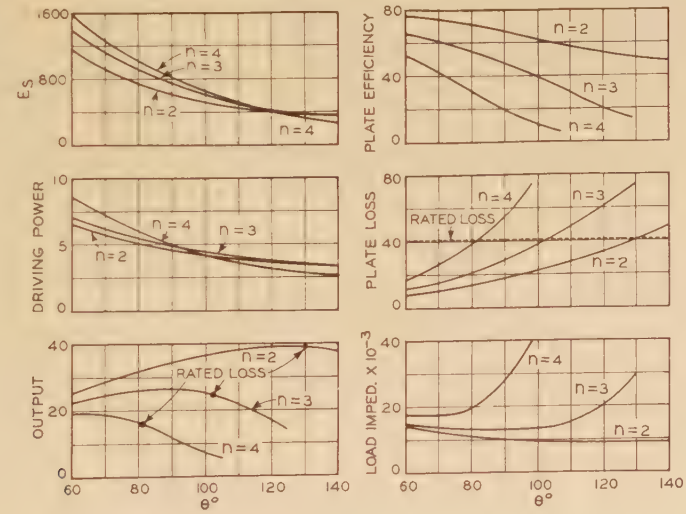


Figure 5. Curves showing the performance of a typical tube operated as a harmonic generator under various conditions

The division of these components between grid and plate electrodes can be determined by the fact that when secondary electron emission at the grid is not excessive (as is normally the case), the pulse of grid current can be considered as approximating a section of a sine wave of fundamental frequency that has been squared.[3] The angle of current flow θ_g for this pulse can be calculated from the equation

$$\cos \theta_g/2 = \frac{E_c}{E_s} \tag{13}$$

The d-c, fundamental-frequency, and harmonic-frequency components of the grid current can now be evaluated in terms of θ_g and the peak grid current, with the aid of figure 2. The d-c plate current is then the d-c component of the total space current minus the d-c grid current, and the harmonic component of the plate current is the harmonic component of the total space current minus the harmonic component of the grid-current pulse. (If secondary emission is large the shape of the grid current pulse is modified. Under such conditions the effect of grid current can be evaluated roughly by estimating the ratio of d-c grid current to d-c component of total space current on the basis of previous experience, and then assuming that the fundamental and harmonic components of the grid current are twice the d-c value.)

It now remains to determine the power relations. The power supplied to the plate circuit is the d-c component of the plate current multiplied by the plate-supply voltage, while the power output delivered to the tank circuit is half the harmonic component of the plate current multiplied by the crest alternating plate-cathode voltage E_L. The ratio of these two powers gives the plate efficiency, and their difference gives the dissipation at the plate. The ratio of the alternating plate-cathode voltage E_L to the harmonic component of the plate current equals the load impedance that the tank circuit must supply.

The grid bias can be calculated by the following formula derived from conventional theory:

$$\text{Grid bias} = E_c = \frac{E_B(1 - \cos n\theta/2) + E_{\min}\cos n\theta/2}{\mu(1 - \cos\theta/2)} + \frac{E_{\max}\cos\theta/2}{1 - \cos\theta/2} \tag{14}$$

The peak exciting voltage is $E_c + E_{\max}$, and the grid driving power is this peak exciting voltage multiplied by half the fundamental-frequency component of grid current.

An example illustrating the details of the calculation procedure is given in the appendix.

Discussion of Factors Involved in Design of Harmonic Generators

The most important operating characteristics of a harmonic generator are the harmonic power delivered to the tank circuit, the power dissipation at the plate of the tube, and the driving power. The design factors available to control the performance are the angle of current flow, the minimum instantaneous potential $E_{\min}$ reached by the plate, and the maximum instantaneous potential $E_{\max}$ reached by the grid. The influence of these design factors on the performance of a harmonic generator is illustrated in figure 5. A study of this figure, together with figures 2 and 3, brings out the salient features involved in harmonic generator behavior. *First*, for a given peak space current* and harmonic, the power output will be maximum when the angle θ of current flow based on the fundamental frequency is approximately 260°/n. The maximum is not critical however, and angles of flow differing from this by as much as ±40 per cent give good output. *Second*, the plate efficiency of the harmonic generator is increased by reducing the angle of current flow to a value smaller than that giving maximum output because this causes the d-c component of the total space current, and hence the input power, to decrease faster than the output falls off. It is also to be noted that the plate efficiency of a harmonic generator will be considerably less than for the corresponding class-*C* amplifier unless the angle of flow is appreciably less than the value for maximum output. *Third*, the values of $E_{\min}$ and $E_{\max}$ not only must be such as to draw the maximum allowable space current, but should also normally have a ratio $E_{\max}/E_{\min}$ somewhat less than is customary in class-*C* amplifiers in order to keep the grid current, and hence the driving power, low in spite of the large exciting voltage required. *Fourth*, the driving power increases as the angle of current flow is reduced, and becomes excessive at angles of flow as small as 60 to 70 degrees. Because of this the driving power is as much a limiting design factor in harmonic generators as is the plate loss and power output. *Fifth*, the load impedance that the tank circuit must supply is greater for harmonic generators than for the corresponding class-*C* amplifier, and becomes greater the higher the order of harmonic. This results from the fact that for proper operation the voltage across the tank circuit is independent of the harmonic whereas the output power is less the higher the harmonic. With a given effective tank circuit *Q* this means that the *L*/*C* ratio should be higher for harmonic generators than class-*C* amplifiers. *Sixth*, the output power obtainable in second harmonic generation is about $^2/_3$ of the output that the same tube will develop as a class-*C* amplifier, and for higher harmonics the output is roughly inversely proportional to the order of the harmonic. *Seventh*, the fact that output goes down and driving power goes up as the order of the harmonic is increased makes it unwise to attempt harmonic generation above the third or fourth harmonic under ordinary conditions, since with fifth harmonic operation the driving power can be expected to be of the same order of magnitude as the power output.

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* The allowable peak space current is determined by the cathode emission, assuming a reasonable factor of safety. Manufacturers have not, however, established peak current ratings for their tubes. Until this is done the designer may assume that the peak current rating approximates four to five times the sum of d-c plate and grid currents obtained with recommended class-*C* telegraph operation.

Accuracy

The accuracy of the analysis that has been developed for harmonic generators is entirely adequate for ordinary design purposes. The principal assumption involved is that the total space current of the tube is proportional to $(E_g + E_p/\mu)^\alpha$, where μ and α are constants. If the values of μ and α are taken for conditions corresponding to a fairly large total space current experience[2] shows that the errors introduced by considering α and μ constant are quite small even though α and μ vary appreciably as cutoff is approached. The method of handling grid current also involves some approximation, but this is unimportant, particularly if there is no secondary emission. In any case the action of grid current is in itself only a second-order effect and therefore need not be determined with precision. The neglect of the D^2 term in obtaining equations (11) and (12) also introduces some error, particularly when θ exceeds $260°/n$, but since the values of k encountered in practice are usually less than 0.5, the error in the actual pulse of total space current from this approximation will reach five per cent only in the most unfavorable cases.

Under ordinary conditions the analysis can be expected to give calculated plate loss, output power, and plate current, correct within about five per cent unless the angle of flow is exceptionally large for the harmonic involved, or unless there is excessive secondary electron emission at the control grid. Even then the accuracy to be expected is normally within ten per cent, which is of the same order of magnitude as the variations in the characteristics of individual tubes of the same type from the published characteristics.

Table I. Agreement Between Calculated and Exact Harmonic-Generator Performance

Conditions: Type 204-*A* tube, $E_B = 1{,}500$, $E_{\max} = 250$, $E_{\min} = 375$, $I_m = 1.26$ amperes, peak grid current = 225 milliamperes, θ = 100 degrees, $n = 3$, $E_c = 751$ volts

	Approximate	Exact
D-c plate current (milliamperes)	189	196
D-c grid current (milliamperes)	27	20
Power input (watts)	284	294
Power output (watts)	105	102
Driving power (watts)	26	19
Plate loss (watts)	179	192
Plate efficiency (per cent)	37	35

A comparison of the performance as calculated by the method that has been developed, with the exact performance is given in table I for a typical case.

Appendix

Example of Design and Calculation of a Harmonic Generator; Comparison With Exact Performance

In order to show how the above analysis is applied, assume that it is desired to obtain third harmonic generation from a type 204-*A* tube operating at 1,500 volts, having $\mu = 23$, and a normal rated plate dissipation of about 200 watts. This tube is not the most satisfactory one for demonstrating the accuracy of the method of analysis that has been developed because the published characteristics of the 204-*A* tube show more secondary electron emission at the grid than do most air-cooled tubes. However, it is selected because it is one of the few tubes for which the published characteristics are sufficiently complete to permit checking of the approximate analysis by exact point-by-point calculations. Most of the so-called "complete" characteristic curves of transmitting tubes found in tube manuals are not extended to high enough plate potentials to cover the full operating range commonly used in harmonic generators.

The first step in the design is the selection of a suitable peak space current and corresponding values of $E_{\min}$ and $E_{\max}$. Reference to the data supplied by tube manufacturers indicates that $I_m = 1{,}260$ milliamperes will be satisfactory, and that this could be obtained by $E_{\min} = 375$, $E_{\max} = 250$. With this combination the peak grid current will be 225 milliamperes, which is small enough to keep the driving power low, and yet at the same time $E_{\min}$ will be small compared with the plate-supply voltage.

The next step is the selection of a value of θ. From the discussion given in the paper, combined with an examination of figure 2, it appears that $\theta = 100$ degrees would be reasonable. With this value of θ, and assuming a 3/2-power law, figure 2 then gives $I_0/I_m = 0.161$, and $I_n/I_m = 0.177$. The fractional corrections that figure 3 indicates would be applied to these for a 3/2 law and for $k = 1$ are -0.33 for the d-c term and -0.060 for the third-harmonic component. However, as k is $[(1{,}500 - 375)/23]/250 = 0.20$ the actual corrections are -0.065 and -0.012, respectively. The d-c and third-harmonic components of the total space current are then $1{,}260 \times 0.161\ (1+0.065) = 216$ milliamperes, and $1{,}260 \times 0.177\ (1+0.012) = 226$ milliamperes, respectively. From equation (14) the grid bias is found to be 751 volts, which makes the peak signal voltage 1,001 volts. The angle θ_g of grid-current flow is then given by equation (13) as 82.8 degrees. Assuming a square-law grid-current pulse, reference to figure 2 shows that for a peak grid current of 225 milliamperes, the d-c, fundamental-frequency, and third-harmonic components of the grid current are 27, 52, and 39 milliamperes, respectively. As the peak signal voltage is 1,001 volts the grid driving power is $1{,}001 \times 0.052/2 = 26$ watts. If grid-leak bias is used the leak resistance is $751/0.027 = 28{,}000$ ohms. Next, subtracting the d-c and third-harmonic components of the grid current from the total space current, gives 189 milliamperes, and 187 milliamperes, respectively, as the d-c and third-harmonic components of the plate current. This calls for a tank-circuit impedance of $1{,}125/0.187 = 6{,}000$ ohms. The power input to the plate is 284 watts while the third-harmonic power delivered to the tank circuit is $0.187 \times 1{,}125/2 = 105$ watts. The plate efficiency is hence 37 per cent while the plate dissipation is 179 watts. Inasmuch as this loss is slightly less than the rated value for normal operation, the assumed $E_{\min}$, $E_{\max}$, and θ represents a suitable operating condition.

The performance of this harmonic generator for the same E_B, $E_{\min}$, $E_{\max}$, and E_c has been calculated exactly by graphical integration of curves such as shown in figure 1 drawn on the basis of tube characteristics given in the tube manual. The results are given in table I, and show

The Electric Strain Gauge

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MANY new developments have grown out of the vibration recorder[1] originally described before the AIEE in 1926. One of the first of these developments resulted in apparatus for recording transient pressures electrically.[4] This has been used to measure transient pressures in switchgear apparatus, transformers, water wheels, steam turbines, gasoline engines, refrigerators, and in other places. Another is the electric gauge[8,18] which has many applications. It is used for the most accurate gauging of production parts in machine shops and inspection rooms, also it is widely used in steel mills for continuous gauging of strips as they are being rolled, for controlling their thickness, for measuring the tension in the strip[19] and the pressure applied to the mill rolls. Another application is the measurement of the thickness of paint, enamel, or other nonmagnetic coatings over steel.[13]

The electric strain gauge is an instrument for measuring mechanical strains electrically. Electrical, mechanical, and civil engineers have used it very successfully. It has proved its value in the study of stresses in railroad tracks and in bridge members as locomotives pass over them and in determining the lateral thrust produced by the axles of the locomotives.[14]

Electric-locomotive designs have been greatly influenced by the results obtained from these gauges. It is equally useful in measuring the strain in machine parts when they are subjected to stress.

Originally these developments used an oscillograph to produce records in which a 500-cycle wave was modulated, figure 5 (*a*). The envelope of the wave showed the variations in the quantity being recorded. In order to obtain accuracy the deflections were necessarily large and the number which could be recorded on a single film without overlapping each other was correspondingly small.

The record obtained from the electric strain gauge is a single-line trace of the varying strain in the part to which the gauge is attached. Several of these curves can be recorded on a film, figures 5 (*b*) and (*c*), even though the deflections are comparatively large. This makes it possible to obtain greater sensitivity without introducing difficulty in interpreting the records.

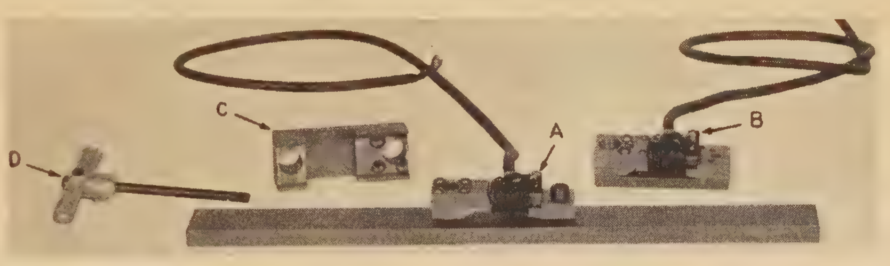

Figure 1

A—Strain-gauge head mounted on a test bar
B—Balancing unit
C—Attaching fixture

The electric strain gauge, shown in figures 1 and 2, has a circuit fundamentally the same as that of the vibration recorder.[1] The four arms of an a-c bridge circuit, figure 3, contain, respectively, a strain-gauge head, a balancing unit and two coils of a differentially connected transformer. The two differential transformer coils will have zero drop across them when the strain-gauge head and the balancing unit have about the same air gaps. The air gap of the balancing unit remains fixed while that of the strain-gauge head varies according to the strain in the piece of apparatus under investigation. The voltage drop across the differential transformer varies with the changes in the air gap of the strain-gauge head and the deflections of the oscillograph galvanometer are proportional to these.

The strain-gauge head *A*, figure 1, is shown mounted on a test bar and its balancing unit *B* is at the right. *C* is a mounting fixture used to align the gauge head while attaching it to the work. Changes in length of the test bar vary the air gap between the two parts of the magnetic circuit of the gauge head. In figure 2 is shown a four-circuit power unit for use with four strain-gauge heads and their balancing units. The four oscillograph galvanometers and the necessary 2,000-cycle excitation are also connected

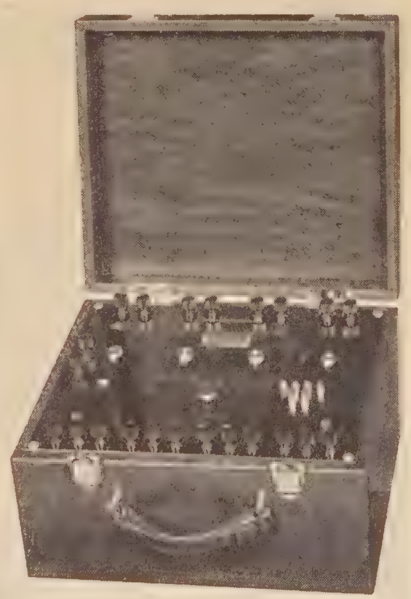

Figure 2. Power unit for use with four strain-gauge heads

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1. For all numbered references, see list at end of paper.

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an agreement entirely satisfactory for design purposes even in spite of the fact that the 204-*A* tube has considerable secondary electron emission at the control grid. This secondary emission makes the grid-current pulse more peaked than a square law, thereby reducing the d-c grid current below the calculated value while raising the d-c plate current, but without affecting the third-harmonic component of grid and plate currents appreciably. If it were not for these effects of secondary emission the agreement between calculated and exact results would be within three per cent, but even as it is the errors in calculated power output and plate loss are less than seven per cent.

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to the power unit, producing a record of four strains simultaneously. For convenience in operating in the field a 2,000-cycle generator driven by a 12-volt motor is operated from a 12-volt storage battery, figure 3. Where a power supply is available, the 2,000-cycle generator can be driven by a standard motor.

The principal difference between the old vibration recorder and the new strain gauge lies in the oscillograph galvanometer circuit. This circuit includes, in addition to the galvanometer, a copper-oxide rectifier, a 2,000-cycle filter, and a 4,000-cycle filter. The galvanometer circuit must have a low impedance for all frequencies within the range in which mechanical phenomena occur, as for example, from one to 1,000 cycles per second. Most mechanical apparatus on which strain gauges would be used will have natural frequencies well within this range.

In order to obtain relative values for the various frequencies to be recorded, it is necessary to use a galvanometer filter circuit that will give all frequencies approximately the same weighting. In other words, the output circuit impedance should be the same for all frequencies within the range in which the circuit is to be used.

A typical frequency-impedance curve is plotted in figure 4, showing that the impedance remains approximately the same up to 1,000 cycles per second, ranging from 125 to 180 ohms. Mechanical deflections in the range from 1,500 cycles to 2,200 cycles will be recorded at greatly reduced values as these fall within the resonant zone of the 2,000-cycle filter, which is designed with a high impedance to eliminate the 2,000-cycle excitation of the generator. A 4,000-cycle filter circuit is used to eliminate the 4,000-cycle ripple.

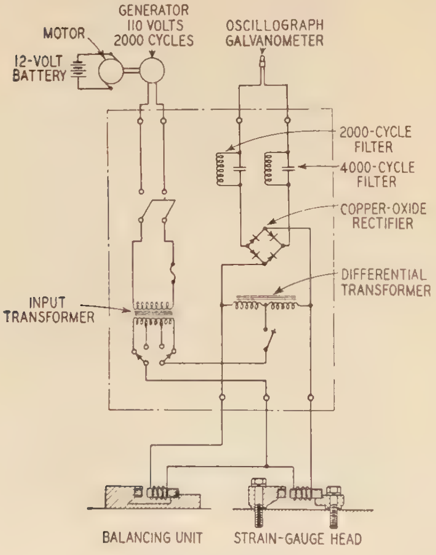


Figure 3. Schematic diagram of electric strain gauge

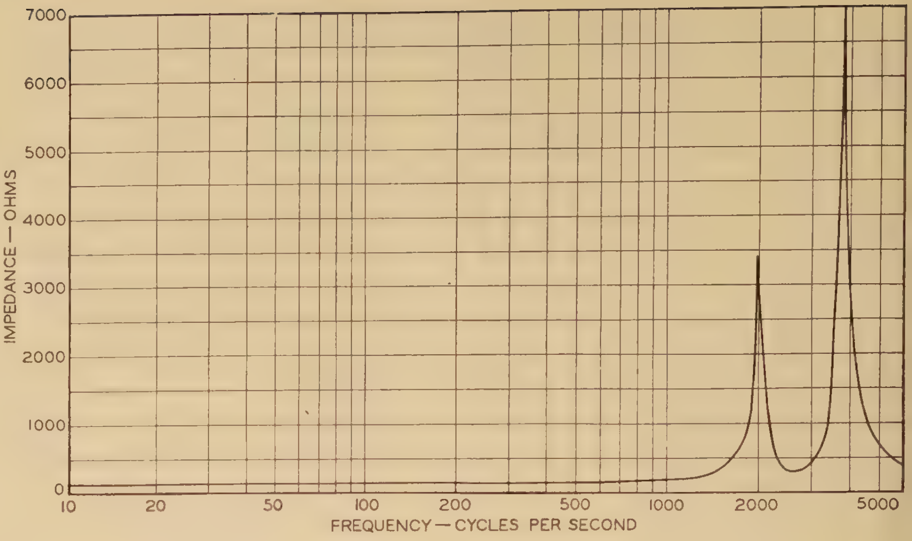


Figure 4. Frequency-impedance curve of oscillograph-galvanometer filter circuit of electric strain gauge

The two high-impedance peaks in figure 4 come at 2,000 cycles and at 3,800 cycles per second, where the circuit is in resonance for the purpose of eliminating the excitation frequencies. The impedance at these two frequencies are approximately 3,400 ohms and 7,000 ohms, respectively.

In order to clarify the results of producing a pure d-c record from an a-c excitation source, let us consider what is going on within the oscillograph-galvanometer filter circuit. The copper-oxide rectifier receives a 2,000-cycle alternating current for its input, which contains equal amplitudes for each of the individual half cycles provided there is no mechanical disturbance being investigated. When mechanical transients occur, the individual half cycles vary in amplitude in proportion to the disturbances which are being measured. In other words, the 2,000-cycle carrier wave is modulated by the mechanical phenomena. The copper-oxide rectifier receives this modulated 2,000-cycle wave and has for an output a modulated pulsating wave. The pulsations from the rectifier are eliminated from the galvanometer circuit by the 2,000-cycle and the 4,000-cycle filters, thus producing a d-c deflection.

A Fourier Series analysis of the rectifier pulsations shows a d-c component, a fundamental of 4,000 cycles, a lower frequency component of 2,000 cycles, and harmonics higher than 4,000 cycles. An oscillographic analysis of the galvanometer circuit shows that the galvanometer itself produces considerable mechanical damping as the natural frequency of the supersensitive galvanometer used is approximately 1,200 cycles per second. The 4,000-cycle filter when used alone leaves a 2,000-cycle ripple on top of the d-c deflection. This 2,000-cycle ripple comes from the rectifier and the magnetic pick-up in the circuit. The 4,000-cycle filter and the 2,000-cycle filter, together with the mechanical damping of the galvanometer, produce a d-c deflection which is practically free from alternating current.

The oscillogram, figure 5 (*b*), shows a record of the mechanical transient which occurred in a test bar when subjected to a sudden blow. Curve *B* shows this transient as recorded by the strain gauge. Curve *C* shows the corresponding 2,000-cycle transient supplied to the rectifier. Curve *A* is a 60-cycle timing wave. Strain-gauge records such as curve *B* can be easily identified even when they overlap each other. It is possible to record six such curves simultaneously when using a six-element general-purpose oscillograph. Figure 5 (*c*) shows five records which can readily be distinguished from each other at all points.

The strain-gauge head *A*, figure 1, must be calibrated very accurately in order to measure the small changes in length of the part under test. For this purpose it is mounted at *A* on a calibrating stand, figure 6, just as in actual use, with the balancing unit *B* in the second leg of the bridge circuit, figure 3, of which the remaining two legs are in the power unit, figure 2. It is customary to make this calibration in ten-thousandths of an inch (0.0001-inch steps) although less accurate calibrations are sometimes sufficient. An electric gauge *E*, figure 6, is used with its power unit *F* and indicating microammeter *G* as a calibrating

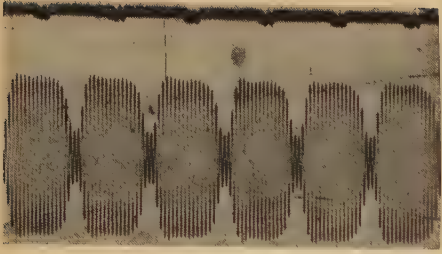


Figure 5a. A modulated 500-cycle record

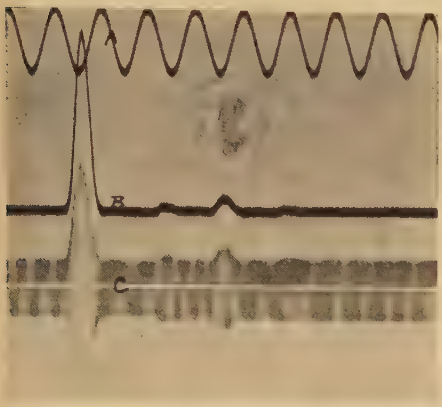


Figure 5b. Strain-gauge record

A—Timing wave, 60 cycles
B—Mechanical transient, impressed on the electric strain-gauge circuit
C—2,000-cycle a-c input to copper-oxide rectifier

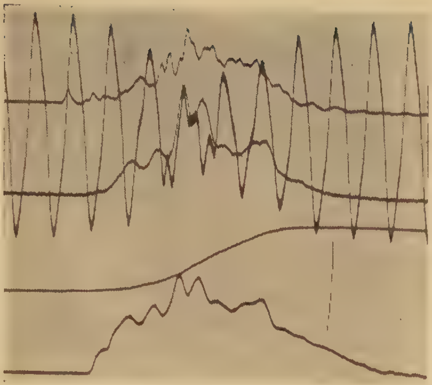


Figure 5c. Simultaneous records using electric strain gauges and vibration recorder

medium. A 2,000-cycle power supply is used for excitation and an oscillograph galvanometer for recording in order to be able to apply the calibration to rapid changes which may occur while the strain gauge is being used. The calibration is made by taking readings of oscillograph deflections corresponding to a number of definitely spaced settings of the strain-gauge head. The indicating instrument *G*, figure 6, which is used with the electric gauge *E*, gives a full-scale deflection for 1/1,000 inch movement at the strain gauge, a magnification of 5,000 to one. Provision is made on the calibrating stand for comparing the electric gauge directly with accurate thickness standards.

After calibrating the strain-gauge head on the stand, it can be moved to a test position without changing its calibration when its air gap is reset to give the same oscillograph deflection.

A typical calibration of a strain-gauge head is shown in table I. This calibration was taken with air gaps of approximately 0.010 inch in the strain-gauge head and balancing unit. It is here seen that a strain of 1/100,000 inch produces an oscillograph deflection which is easily read. Corresponding calibrations with larger air gaps can be taken if less sensitivity is desired in order to cover a wider working range.

The calibrations of table I are made statically, but they can be applied to transient measurements over the frequency range for which the instrument was designed. The variations in air gap of the strain-gauge head produce changes in impedance of that branch of the bridge circuit which are independent of their rate of change and should be recorded correctly if they are within the frequency range of the electric gauge and of the oscillograph galvanometer used. In order to obtain high current sensitivity a supersensitive oscillograph galvanometer is used for recording. This can be used up to at least 500 or 600 cycles per second without correction. A transient such as that shown in curve *B*, figure 5 (*b*), was over in $^1/_{80}$ second so that it was well within the working range of the oscillograph galvanometer. Errors due to change of damping of the oscillograph galvanometer with change of temperature are practically eliminated due to the fact that the comparatively low frequency of the modulated wave is recorded instead of the higher carrier frequency.

If only static or slowly varying strains are to be recorded, a carrier frequency lower than 2,000 cycles is satisfactory de-

Table I. Calibration of Strain-Gauge Head

Master Gauge Blocks, Nominal Thickness (Inches)	Thickness (Inches)	Microamperes	Oscillograph Galvanometer Deflections (Millimeters)
0.1000	0.10000	100	11
0.1001	0.10006	121	15
0.1002	0.10019	157	22.5
0.1003	0.10028	187	28.5
0.1004	0.10036	205	32.
0.1005	0.10048	250	41.
0.1006	0.10060	288	48.5
0.1007	0.10068	312	53.5
0.1008	0.10079	349	61.
0.1009	0.10090	388	68.5
0.1010	0.10099	423	75.5

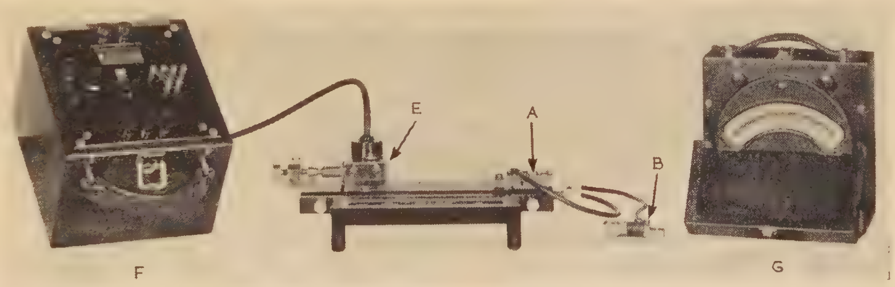
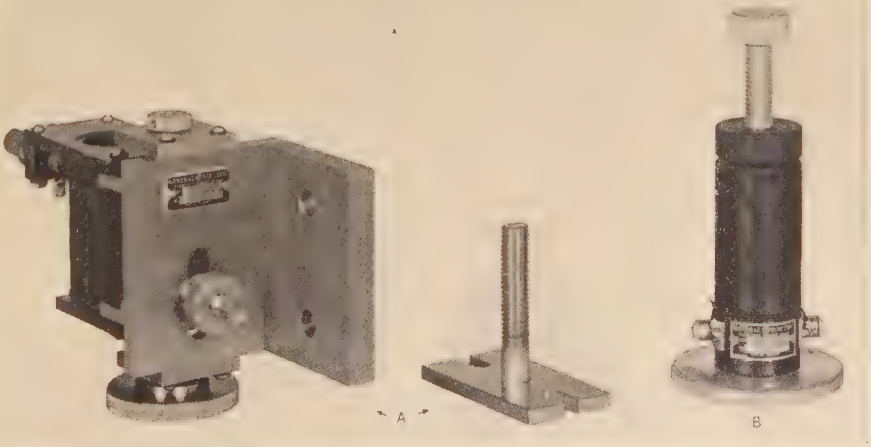


Figure 6 (above). Strain gauge calibrating equipment (power unit at left, calibrating stand and gauge heads in center, indicating instrument at right)

Figure 7 (below)

A—Travel recorder detector
B—Balancing unit



pending upon the rate of change of the stress. An indicating instrument can be substituted for the oscillograph galvanometer to show the magnitude of static strains only.

In connection with the measurement of strain, it is frequently desirable to determine the relative movement of parts. A travel-recorder detector, designed to measure deflections up to one inch, is shown in figure 7 together with its balancing unit. These are substituted for the strain-gauge head and balancing unit of figure 3, producing a record comparable with that from the strain gauge. It is used with the oscillograph when very rapid changes are to be recorded or with an indicating instrument to show slower movements.

The armature, shown in the middle of figure 7 is mounted on the moving part and the frame of the detector on the stationary part so that one moves with respect to the other. The deflections on the oscillograph film are directly proportional to the mechanical motions and are unidirectional with respect to the electrical zero.

Summary

The electric strain gauge can be used to record accurately strains as low as 0.00001 inch, whether these are static or are oscillatory at frequencies up to at least 500 cycles per second, and the single-line trace allows several measurements to be recorded simultaneously.

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Discussion

C. M. Hathaway (General Electric Company, Schenectady, N. Y.): This paper is intended by its authors to serve as a progress report to the Institute and it should be welcomed because a great deal has been accomplished since the original presentation by A. V. Mershon, one of the co-authors of the present paper, in 1926, in a paper entitled "Vibration Recorder for Electrically Measuring and Recording Small Mechanical Movements."

Although the device originally described by Mr. Mershon has received numerous modifications since that time as its application has been extended in many different directions, the same fundamental circuit still survives. This present paper described the extension of the application of the gauge to measurements at higher frequency, the addition of a filter to provide a more desirable type of record as well as a more accurate one, and the application of the gauge to the measurement of strain.

The applications of the electric gauge since its original conception have been numerous, and they are, I believe, just as interesting to engineers in all branches of our profession, so I will present a little historical sketch of its development from infancy to the present time, and describe some of its interesting and more recent applications.

The fundamentals of the electric gauge were first worked out in order to measure the motion of hydraulic gate valves under water. The principle was applied shortly thereafter to the measurement of transient pressures in oil-circuit-breaker housings and to the measurement of the displacements of rotating parts within turbine housings. About this time a refrigerator manufacturer was in need of an accurate gauge for the production measurement of compressor parts having tolerances of "plus nothing—minus 0.0003 inch." The electric gauge principle was naturally applied to this problem also and with very satisfactory results, $^1/_{10,000}$ inch being expanded to one inch on the scale of the indicating instrument. The refrigerator manufacturer was enabled to inspect his parts more accurately and rapidly than before, and actually to assort his parts for matched assembly within his small tolerance range. Special multiple gauging stands were built, permitting as many as four dimensions to be gauged simultaneously. Points of wear were tipped with tungsten carbide, diamond, or sapphire, and some of the original stands have been in continuous use since 1930 and are still in operation.

The successful operation of these gauges in the plant of the refrigerator manufacturer so impressed a gauge manufacturer that an arrangement was made for supplying the electric gauge to the trade, so that the electric gauge is now well known and is found in many manufacturing plants throughout this country and parts of Europe.

An interesting application of the electric gauge has been made to the tail-stock of the Pratt and Whitney measuring machine enabling this machine to be used for comparison work to a millionth of an inch if proper precaution is taken in regard to constancy of temperature.

Perhaps to the engineer the most interesting and useful application of the electric-gauge circuit is to the measurement of strain. Strain gauges have been built and used with good results in a number of investigations involving the measurement of stress in mechanical and structural members. Studies have been made of stresses in bridge structures during passage of high-speed locomotives, enabling the engineers to study stresses in structures too complex to permit ready calculation, and to investigate the resonant behavior of the bridge as trains crossed it at various speeds. Investigations have been made of stresses in electric locomotive members during service, and of stresses in rails and joint bars under various normal and abnormal conditions. Most of these investigations were carried on with a strain gauge weighing between four and five ounces and having a gauge length of $2^1/_4$ inches. This gauge is sensitive enough to permit measurement of stress as low as 100 pounds per square inch in steel, without the use of amplification.

A recent development in this strain gauge makes use of amplification, not to increase sensitivity but to decrease the size of the gauge head. The result is a gauge head weighing about one-half ounce and having a gauge length of an inch. This small strain gauge is particularly useful for measurement of stresses in aircraft parts and members of small section.

The electric gauge has been applied to cold-strip-steel rolling with surprising results. By the electric gauge the thickness of the finished product is continuously indicated, the pressure exerted on the rolls is measured, and the tension on the strip between stands is both indicated and automatically controlled. These applications of the electric gauge have alone increased the rolling speed from about 250 feet per minute to more than 1,300 feet per minute.

"De-ion" Air Circuit Breakers for A-C Feeder, Motor Starting, and Station Auxiliary Service

By R. C. DICKINSON
ASSOCIATE AIEE

Synopsis: The first circuit interrupters for a-c service were of the air-break type, followed very shortly by oil circuit breakers for general high-voltage service. Air "De-ion" circuit breakers introduced in 1928 provided a new type of circuit interrupter for a-c service. Recent applications of these principles result in a line of De-ion air circuit breakers for 2,500-volt and 5,000-volt ratings suitable for use in a-c feeder circuits, motor starting, and general station auxiliary service.

THE electrical industry used air-type arc-interrupting devices when it first became desirable or necessary to open the circuits between the generators and the loads. Very little was known about arc characteristics except that after an arc was stretched sufficiently, the circuit voltage would not maintain it and the circuit would be interrupted. In about 1895 the increased voltage and power requirements incidental to the extension of a-c systems led to the introduction of the oil circuit breaker on account of its compactness and the confinement of the arc. Both air and oil circuit breakers continued in use for several years, but the advantages of the oil breaker led to the disappearance of the air breaker from the higher voltage a-c fields. The older catalogues indicate the use of air circuit breakers for voltages up to and possibly higher than 66-kv as late as 1902. Figure 1 illustrates this general type of construction as applied to 2,300-volt service.

The oil circuit breaker gradually became the principal factor in high-voltage a-c switching. Nevertheless, the air circuit interrupter has continued for application to d-c service as high as 3,000 volts and for a-c service of 2,300 volts and in some cases at higher voltages. The magnetic blow-out principle was introduced as a modification of the "long arc" principle of circuit interruption and these devices continue in use for moderate power requirements.

The steady growth of the electrical industry resulted in continually increasing concentrations of power and an ever-growing necessity for continuity of service, requiring greater safety and dependability of operation, particularly on the part of the switchgear. Improvements were made in the construction of oil circuit breakers to meet these increasingly severe operating conditions and research was directed into the fundamental principles of a-c circuit interruption.

As a result of this research, the "De-ion" air circuit breaker principle was introduced in 1929[1,2]. This De-ion air-break principle was based on a new concept of arc phenomena resulting from intensive studies of the fundamental structure of matter, which work, of course, had been going on for a good many years.

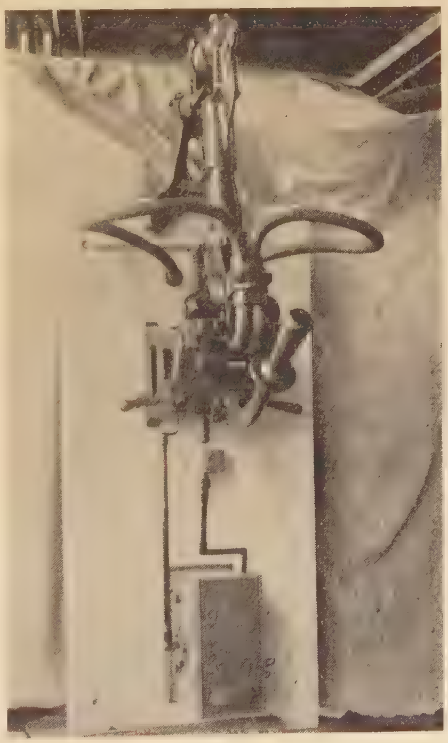

Figure 1. High-voltage 2,500-volt air circuit breaker used as late as 1902 to 1904

Because of the fundamental soundness of the De-ion theory, it then became possible to design circuit breakers for a definite performance. The inherent advantages of De-ion air circuit breakers over other types of air circuit breakers were found to be chiefly compactness, relatively high arc rupturing ability, short duration of arcing, and the control of arc products, and thus opened up new possibilities of switchgear without oil for 25,000 volts and below, and at moderate interrupting capacities.

To review briefly the theory of the De-ion air circuit breaker, its operation depends primarily upon the high initial rate of recovery of dielectric strength of a thin space at an arc cathode, this being in the order of 250 volts within the first microsecond. If a series of N arc spaces is provided, a voltage of 250 N can be interrupted on commercial circuits although a lower voltage per arc space is used in actual practice. Since the interrupting process depends primarily upon the rapid development of a very thin layer of dielectric at the arc cathode, it follows that the individual arcs in the series need not be long and in fact they may be as short as is commercially practicable. The net result is that in a 2,500-volt 100,000-kva De-ion air circuit breaker, capable of interrupting the full 2,500 volts on a single element, the length of the active parts of the interrupter is less than six inches.

In general, the duration of arcing in De-ion air circuit breakers averages from one-half to one cycle at the usual range short-circuit currents. The arc is quickly moved from the arc tips into the interrupting element and the circuit is generally interrupted at the next zero point of current.

The interrupting element of the De-ion air circuit breaker, being composed essentially of a series of copper plates separated by thin insulating spacers, completely encloses the arc and the latter is never exposed to the exterior parts of the breaker. By the proper design and choice of materials it is thus possible to control the expanding gases resulting from the arc. As a result, the De-ion air circuit breaker has been adapted to metal enclosed switchgear which compares favorably in size to corresponding oil switchgear.

The first practical design of a De-ion air circuit breaker was at 2,300 volts. This breaker was not commercialized but several were placed in trial operation on transformer and motor circuits in the East Pittsburgh plant in August 1927.

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[1] For all numbered references, see list at end of paper.

Two of these units are still in active service.

The next design of De-ion air circuit breaker was in the 15-kv class, with an interrupting rating of 20,000 amperes, equivalent to 500,000 kva. Approximately 100 of these breakers were placed in central station service between 1928 and 1932, the earliest of these units still being in operation with the original interrupting elements.

Many other interesting applications of the De-ion principle have been made for 5,000-volt, 7,500-volt, 15,000-volt, and 25,000-volt classes. However, this apparatus has in general been more costly to build than corresponding oil breakers and the great increase in oil breaker efficiency in recent years has removed to a large degree the necessity for duplication of apparatus lines.

Since De-ion grids not only became available for new oil circuit breakers, but also were applicable to circuit breakers in the customer's possession, the advantages of the De-ion air circuit breaker became less apparent. However, with the accumulation of field experience with these early De-ion air breakers, certain fields proved logical ones for the exploitation of the De-ion principle:

(*a*) Elimination of fuses from low voltage a-c and d-c switchgear has been very general in recent years and the De-ion principle as incorporated in the small line of breakers illustrated by figures 2 and 3 is typical of the apparatus now serving that field.

(*b*) The 6,600-volt three-phase steel-mill main-motor-drive switchgear has proved a fertile field for De-ion air breakers, because of the fact that these breakers proved their ability to handle highly repetitive service with little or no maintenance. The forward and reverse breakers for main drive motors of 5,000 horsepower at 6,600 volts, are in some cases required to operate 1,500 to 2,000 times per month on starting and full-load currents.

A line of 7.5-kv breakers was introduced in 1933 for this type of service which has since been expanded into metal enclosed equipment of both horizontal draw-out and cubicle construction. Figure 4*a* shows a 1,200-ampere 7.5-kv unit for horizontal draw-out equipment rated at 250,000 kva. This breaker is insulated for the AIEE test for 15-kv breakers. In addition to having the long life inherent in the De-ion construction, this line of breakers is also designed for extra long mechanical life. Some of these units have service records of over 150,000 operations as reported in 1937, and are still in active duty. Approximately 150 breakers of this type have been placed in service. Another form of 7,500-volt De-ion air circuit breaker for lower rupturing capacity is shown in figure 4*b*. In this assembly the complete breaker is mounted within a metal enclosure obtaining a high degree of compactness for this type of equipment.

In view of these developments the question may logically be asked, why cannot the De-ion principle be applied rather widely to the elimination of oil from power house auxiliary switchgear and similar installations? The power requirements are well within the technical limits of the De-ion development and there are certain definite improvements in the switchgear layout which can be made by the elimination of oil.

As a result of the large accumulation of field experience on De-ion air circuit breakers, there has been developed a new line of breakers for ratings up to 100,000 kva at 2.5 kv and 150,000 kva at 5 kv. These are particularly applicable to station auxiliary, motor-starting, and substation distribution-feeder service. In this field of switching equipment, space requirements and economic considerations are predominant factors.

Figure 5 illustrates a 2,000-ampere 3-pole 2.5-kv breaker unit of 100,000 kva interrupting capacity. The general design and construction of this breaker differ considerably from that of high-voltage De-ion air circuit breakers previously described before the Institute.[3] The line terminal bushings are mounted on a vertical steel base plate which forms a foundation for the entire breaker assembly. The interrupting elements or deionizing chambers are mounted vertically over the upper terminal bushings,

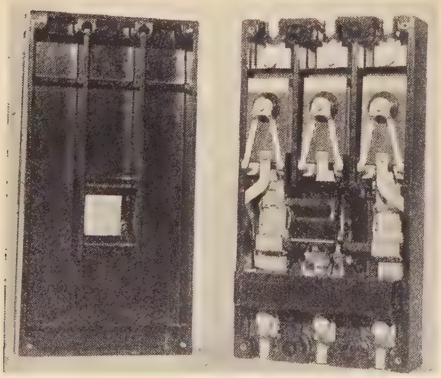


Figure 2. Low-voltage De-ion air circuit breaker, 600 volts alternating current, 250 volts direct current

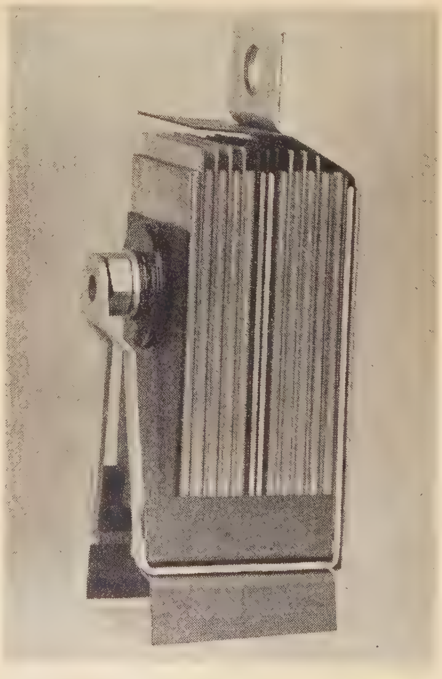
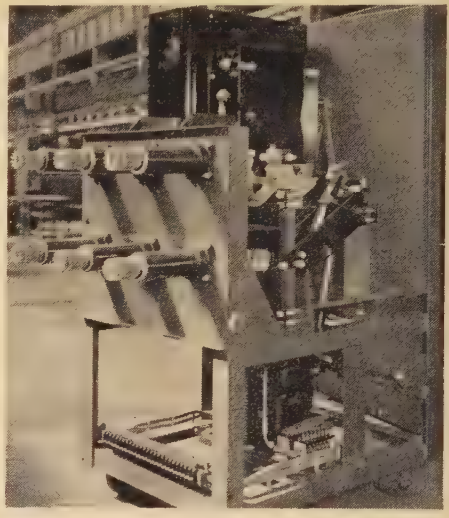
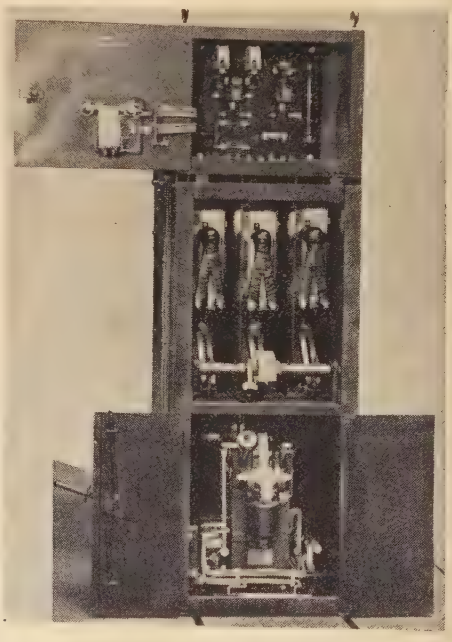


Figure 3. Deionizing chamber for low-voltage De-ion breaker of figure 2



(*a*)



(*b*)

Figure 4. Horizontal draw-out metal-enclosed De-ion air circuit breaker for 1,200 amperes, 7.5 kv, of the type widely applied in 6,600-volt steel mill service

with a small post-type insulator as additional support.

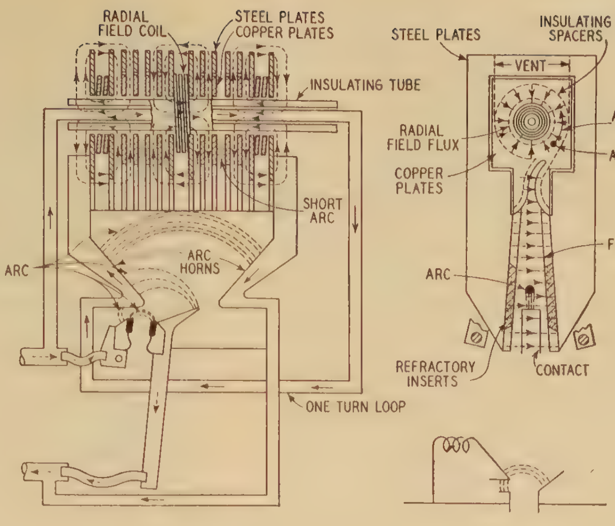


Figure 6. Illustration of the principles of construction of modern De-ion air circuit breakers showing how the arc is controlled by magnetic fields

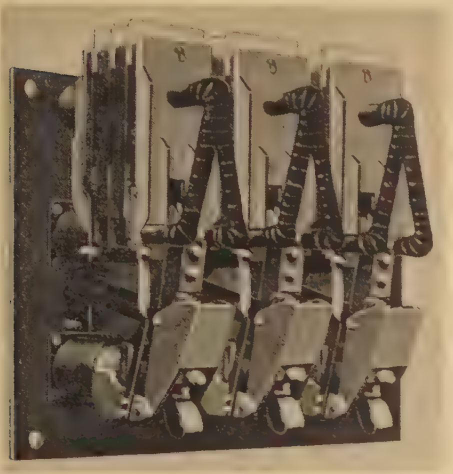


Figure 5. Three-pole De-ion air circuit breaker unit for 2,000 amperes, 2.5-kv, for 100,000-kva interrupting capacity

The principles of construction and operation of the deionizing chamber in this new design of breaker are best understood by reference to figure 6. As in breakers previously described before the Institute, the basic principle of initiating the arc at a single contact and then breaking it into a series of short arcs between copper plates is retained. Also as in previous breakers, two magnetic fields are required, one for moving the arc from the arc tips into the series of plates and another, which in reality is a combination of magnetic fields, for rotating the short arcs over circular paths between the plates. These two magnetic fields are generally referred to as the entering or blow-in field and the radial fields. Referring again to figure 6, each copper plate is surrounded on top and sides by a steel plate of the same thickness. These pairs of plates are stacked with thin insulating spacers between, each set of spacers being so shaped as to form pathways for the individual short arcs and arc terminals and also a vent to the top of the chamber for each short arc. At intervals of a few inches in this stack of plates are located coils for supplying the radial magnetic fields. This unit assembly is clamped tightly together by stiff end plates and insulated studs.

In operation, the steel plates, which extend downward below the arc tips, act as a composite magnetic yoke which supplies magnetic flux for moving the arc through the arc box, the space between the arc tips and the lower edges of the copper plates. This yoke is energized magnetically as follows: As the arc is initially formed at the arc tips, the flux surrounding the arc current circulates through the steel plates above the arc and across the air gap between the lower ends of the steel plates below the arc. This results in a force reaction to move the arc upward toward the copper plates. The shape of the electrical circuit through the line terminal studs and contact members also assists in the initial upward movement of the arc. The impingement of the arc on the tip of the arc horn energizes the loop circuit, formed by the stud running centrally through the copper plates and returning through the two lower studs in parallel, to the arc horn immediately above the stationary arc tip. The arc horn is insulated from the arc tip sufficiently to withstand the voltage drop caused by the impedance through the loop. This is illustrated in the small diagram in figure 6. As the arc strikes the arc horn, the voltage across that portion of the arc between the contact and horn causes current immediately to flow through the loop. Due to the low impedance of the loop compared to the voltage developed by that portion of the arc in parallel with it, the entire current is quickly transferred to the loop. Since the current in the upper stud flows in the same direction as the arc current this loop then acts as an additional turn for further magnetizing the steel plates. With this strengthening of the entering field, the arc is moved upward into the narrowing throat formed by the tapered slots in the copper plates. As explained previously before the Institute, the purpose of the tapered slot in each copper plate is to increase the voltage of the single arc to effect the transition from a single arc to a multiplicity of short arcs in series.

The radial field coils are electrically connected to adjacent copper plates having extensions below the other copper plates. These coils are introduced into series relationship to the arc current shortly before the arc reaches the ends of the slots in the main copper plates, in a manner similar to that in which the entering field loop circuit was introduced. These radial fields then provide additional impetus for the final transfer of the arc, at the ends of the tapered slots, into the stack of copper plates to form a series of short arcs. Under the influence of the same radial fields, the short arcs then rotate at high velocity in the circular pathways formed by the insulating spacers until the next current zero, when the circuit is interrupted.

In the higher voltage De-ion air circuit breakers, the static shields are provided, along the interrupting element or De-ion stack, in order to divide the voltage evenly among the short arcs. Because of the smaller number of gaps and the greater compactness of the interrupting element of the 2,500- and 5,000-volt circuit breaker, satisfactory distribution of voltage is obtained without the use of external shielding.

The contact system of this breaker is interesting in that springs and full-capacity contact shunts are eliminated without sacrificing the basic advantages of the line-type butt contact. Figure 7 illustrates operation of the contacts. The stationary contacts are fixed on the ends of the two terminal studs, the upper one being a replaceable combination main and arcing contact. The movable contacts are located at the ends of a solid copper bar which forms a bridging member across the stationary contacts, the lower pair of contacts being bridged by a light, flexible shunt. The movable contact member is pivoted at the center through an elongated hole to the actuating lever, with a compression spring between the two. This spring biases the movable contact member against the stationary contacts, in the closed posi-

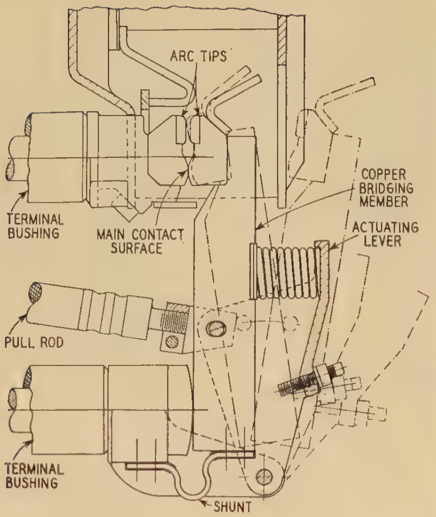


Figure 7. Contact system of the 2.5–5 kv De-ion breaker for station auxiliary and similar applications

tion, and, in opening, gives it a rolling action to cause final separation at the arc tips. These tips are of silver-tungsten, having high resistance against the burning action of the arc.

Solid silver plates in the main contact surfaces maintain low contact resistance over long service periods.

The individual pole units are isolated from each other by insulating barriers of rectangular Micarta tubing. The three-pole breaker is operated by a conventional solenoid mechanism located immediately below the breaker pole units, as shown in the illustration of the test sample, figure 8. Because of its novel arrangement, this breaker is extremely simple and compact and all parts are readily accessible for inspection or maintenance.

An experimental sample 2.5-kv breaker, shown in figure 8, consisting of a single-pole unit mounted on a three-pole frame and operated by a standard three-inch solenoid, was tested beyond its interrupting rating in the high-power laboratory at East Pittsburgh. Tests were made at from less than 50 amperes to well in excess of 25,000 amperes, the majority of tests being made with from 2,500 volts to 3,200 volts on the test generator with restored voltages from 2,000 to 2,600 volts.

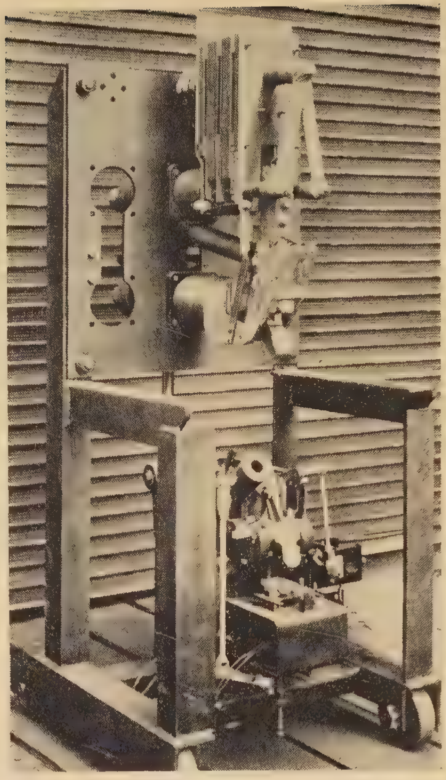


Figure 8. Single-pole experimental model of 2,500-volt De-ion air circuit breaker for 100,000-kva interrupting capacity

Table I. Typical Data From Interrupting Tests on 2.5-Kv De-ion Air Breaker

Test Number	Interrupted Current, Root-Mean-Square Amperes	Restored Voltage, Root-Mean-Square Volts	Time From Energizing of Trip Coil to Arc Extinction (Cycles)
1	220	2,420	7.0
2	323	2,610	6.0
3	1,120	2,060	5.7
4	2,850	2,310	5.7
5	4,160	2,270	5.7
6	7.390	2,200	5.6
7	10.030	2,050	5.3
8	12,000	2,070	5.0
9	14,900	2,290	5.3
10	16,900	2,250	5.2
11	21.100	2,270	5.2
12	20,000	2,200	5.6
13	20,400	2,080	5.5
14	22,200	2,200	5.22
15	25,000	2,510	5.22

The first continuous series of tests consisted of 144 interruptions, stopping only at intervals to examine the breaker. As many of these tests were repeat interruptions at about the same current levels, oscillographic data from a few representative tests are shown in table I. It will be noted that the time from energizing of the tripping coil to the interruption of the circuit is consistently less than six cycles for currents down to approximately 1,000 amperes, showing a safe operating margin for the standard eight-cycle rating.

All of the above tests were made on the sample breaker as originally built and no part of the breaker was modified or replaced during the tests. These tests represent the equivalent of five years or more interrupting service on the average circuit breaker. Figure 9 shows a deionizing plate taken from the experimental breaker after 45 interruptions, 5 of which were above 20,000 amperes, 17 above 10,000 amperes, 23 above 5,000 amperes, and 44 above 1,000 amperes. This plate shows very little deterioration and was used for subsequent tests. Figure 10*a* shows a typical oscillogram made during an interruption of 25,500 amperes at 2.5 kv. Table II shows typical oscillographic data taken from another series of 19 unit-operation interrupting tests.

The experimental breaker was equipped with a deionizing chamber containing a greater number of plates and insulating spacers, designed for an interrupting rating of 20,000 amperes at 5 kv, equivalent to 150,000 kva. Similar interrupting tests were made on this unit. Table III shows typical data taken on this series of tests, with breaker interrupting times of less than six cycles. Figure 10*b* shows a typical oscillogram.

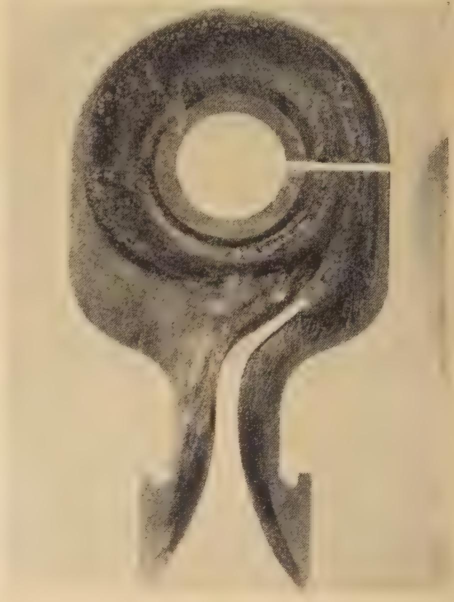


Figure 9. Deionizing plate taken from experimental breaker unit after one series of 45 short-circuit interrupting tests

In addition to the short-circuit interrupting tests, the suitability of this type of breaker for motor starting, station auxiliary, and other types of highly repetitive service was investigated by three series of endurance runs. The first two runs simulated closing the starting current and opening the full-load current of a 1,000-horse power motor. The test condition was made more severe than service condition by using air-core reactors and thus obtaining a power factor of less than ten per cent. The breaker was closed and opened 7,700 times at 235 amperes, 2,300 volts on the single-pole unit. It was then operated 7,700 times on the CO cycle at 1,350 amperes, 300 volts. This total of 15,400 operations was made without any maintenance whatever. The deionizing chamber used in these tests had previously been used in 48 interrupting tests, 20 of which were at from 9,000 to 26,000 amperes. The breaker was in good electrical and mechanical operating condition after these tests.

The third series of tests, part of which was included in the first two series, consisted of a mechanical endurance run of 35,000 operations. At the end of these tests, the breaker was still in good overall condition indicating an ample margin for many years of service.

The breaker unit, shown in figure 5, due to its compactness and small space requirements, is suitable for complete metal-clad or cubicle switchgear designs.

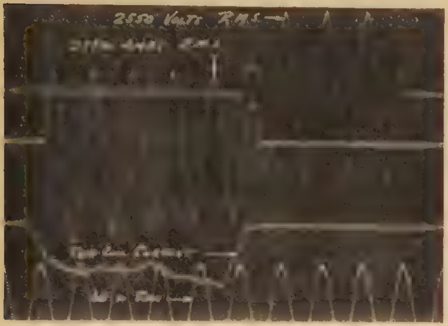


Figure 10a. Oscillogram showing typical interruption at 25,500 amperes—2,510 volts restored on single-pole unit

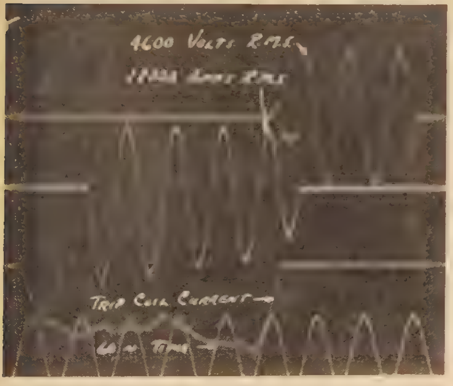


Figure 10b. Oscillogram showing typical interruption at 18,000 amperes, 4,600 volts restored on single-pole unit

Table II. Typical Data From CO Interrupting Tests on 2.5-Kv De-ion Air Breaker

Test Number	Closed Root-Mean-Square Current (Amperes)	Interrupted Root-Mean-Square Amperes	Restored Root-Mean-Square Kilovolts	Time From Energizing of Trip Coil to Arc Extinction (Cycles)
1	1,080	1,050	2.48	5.4
2	3,500	2,430	2.39	5.5
3	4,700	4,180	2.28	5.3
4	11,300	9,070	2.16	5.7
5	17,400	14,400	2.05	5.7
6	17,500	14,400	2.06	5.8
7	18,000	14,700	2.08	5.8
8	40,000	18,800	1.95	5.6

Table III. Typical Data From Interrupting Tests on Five-Kv De-ion Air Breaker

Test Number	Interrupted Current, Root-Mean-Square Amperes	Restored Voltage, Root-Mean-Square Volts	Time From Energizing of Trip Coil to Arc Extinction (Cycles)
1	1,840	4,610	5.7
2	2,910	4,560	5.8
3	3,660	4,380	5.7
4	6,490	4,300	5.7
5	8,000	4,150	5.60
6	12,900	3,890	5.6
7	13,700	3,860	5.6
8	14,900	3,610	5.7
9	16,000	4,000	5.7
10	18,000	3,600	5.8

Figure 11 shows the preferred horizontal draw-out metal-clad switchgear unit with the De-ion air circuit breaker. Uniformity of design is attained by making this unit adaptable for air breakers of various ratings at 2.5 or 5 kv. The insulation is of the 7.5-kv class. By comparison with the equivalent vertical-lift metal-clad unit equipped with a modern oil circuit breaker of 150,000 kva interrupting capacity shown in figure 12, it is to be noted that the space occupied by the De-ion air circuit breaker unit is approximately equal to that for the oil circuit breaker.

In the air breaker unit the high-voltage parts are completely isolated from the low-voltage control circuits by steel barriers. The individual pole units are isolated from each other by rectangular insulating tubes as previously described. Other features of this construction, such as main disconnecting contacts, secondary contacts, insulated bus, etc., follow the most approved construction as applied to modern vertical-lift type metal-clad switchgear with oil breakers. In this unit the De-ion air breaker is horizontally movable to the "disconnect" or test position on rollers near the center of thrust of the disconnecting contacts. From the disconnect position it may be moved out of the cell by means of a small transfer truck, thus permitting convenient removal of the arc interrupting stack for examination and maintenance of the contacts.

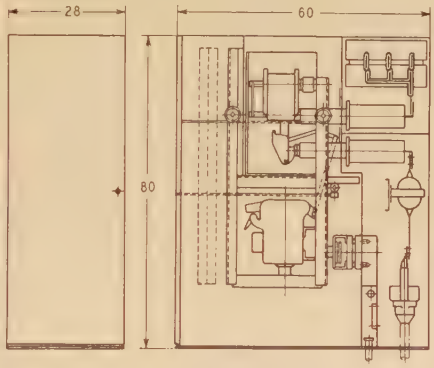


Figure 11. Horizontal draw-out metal-enclosed switchgear unit with De-ion air circuit breaker for 2.5 to 5 kv, 600 to 1,200 amperes, up to 150,000 kva interrupting rating

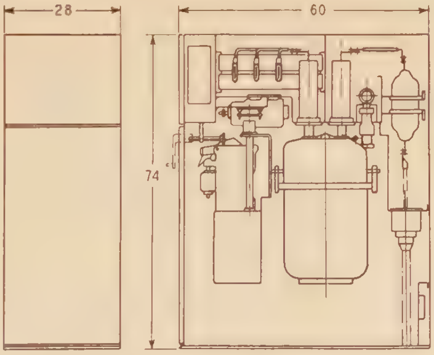


Figure 12. Modern metal-clad switchgear unit equipped with 150,000-kva oil circuit breaker

Potential transformers are located in superstructures for both types of assemblies and in either case control switches instruments, and relays may be accommodated on panels mounted either on the front or the rear of the unit, depending upon whether the front aisle or both front and rear aisles are available.

Previous designs of De-ion air circuit breakers have found wide spread application in steel-mill, arc-furnace, and other highly repetitive services as well as in power-house feeder applications. It is expected that the completion of these new De-ion circuit breakers for lower voltage applications will extend the advantages of this type of construction to power-station auxiliary service, general motor-starting service, and substation-feeder applications.

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2. THEORY OF THE DE-ION CIRCUIT BREAKER, J. Slepian. AIEE TRANSACTIONS, volume 48, April 1929.

3. STRUCTURAL DEVELOPMENT OF THE DE-ION CIRCUIT BREAKER, R. C. Dickinson and B. P. Baker. AIEE TRANSACTIONS, volume 48, April 1929.

Discussion

J. A. Adams (Philadelphia Electric Company, Philadelphia, Pa.). It is particularly gratifying to see continued development of the De-ion air circuit breaker in capacities which can be used extensively in distribution substations. The Philadelphia Electric Company installed two De-ion breakers experimentally in 13.2-kv service in 1931, and in 1934 installed eight more on 4-kv circuits. These have operated successfully under both normal and short-circuit conditions. As a result of this experience it is planned to install three additional breakers in 13.2-kv service, two in 4-kv service, and three in 4.8-kv service this year.

While there may have been a great increase in oil circuit breaker efficiency during the last few years, as pointed out in this paper, it would seem that the nonoil-type breaker has a field of its own regardless of this development. This is implied in the paper by the statement that "there are certain definite improvements in the switchgear layout which can be made by the elimination of oil." A type of installation where it would be particularly advantageous to use nonoil-type breakers appears to be the unattended substations. The authors ask, "Why cannot the De-ion principle be applied rather widely to the elimination of oil from power house auxiliary switchgear and similar installations?" It is not clear why the same line of reasoning should not be extended to the main indoor switchgear. It would seem that a logical development for the nonoil-type breaker is in the higher current carrying and higher interrupting capacity ratings.

Philip Sporn (American Gas and Electric Service Corporation, New York, N. Y.): Mr. Dickinson's paper, describing the 2,500-volt and 5,000-volt "De-ion" circuit breaker development is another indication of the increasing work on the design and the increasing interest in the use of air-type breakers for certain applications, particularly for station auxiliary service. From the description of the design and tests as given in this paper, it appears that an air circuit breaker with very good characteristics and performance has been produced.

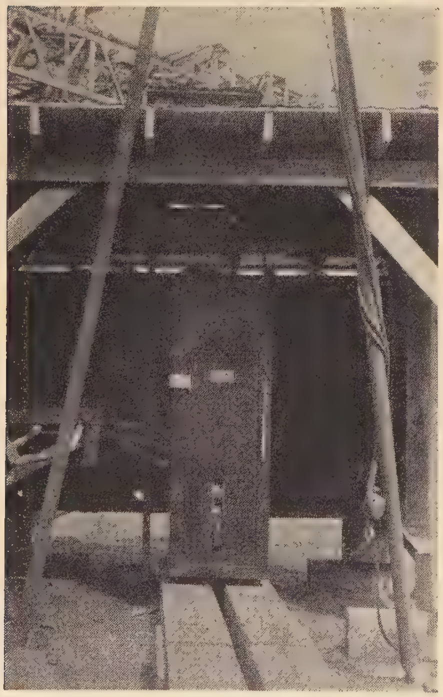
Figure 1. ITE 2,300-volt air circuit breaker set up for tests at Logan

I believe that it would be of interest to present here a brief description of a development along the same lines which was made in connection with the recently completed extension to our Logan, W. Va., plant. When this high-pressure extension to the plant was planned, the engineering and design having been started in 1935, it was felt that because of crowded conditions it would be a decided advantage in the auxiliary service for all of the new portion of the plant to use circuit breakers without oil. Such development had been under discussion for several years with the engineers of the ITE Company. Accordingly, the development of a suitable 2,300-volt air circuit breaker, having a rupturing capacity of 125,000 kva, was launched. The development was completed with the carrying through of a series of tests made at the Logan plant in April of this year.

As compared with the De-ion type of air circuit breaker described by the author, this breaker, developed by the ITE Company, is fundamentally of the magnetic blow-out type, using a special type of arc chute designed for rapid cooling of the arc.

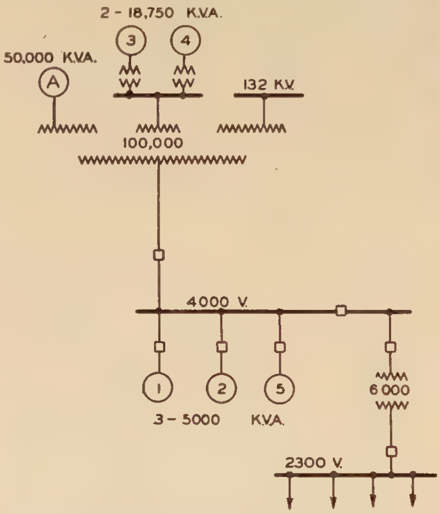

Figure 2. Normal 4-kv and 2,300-volt set-up at Logan

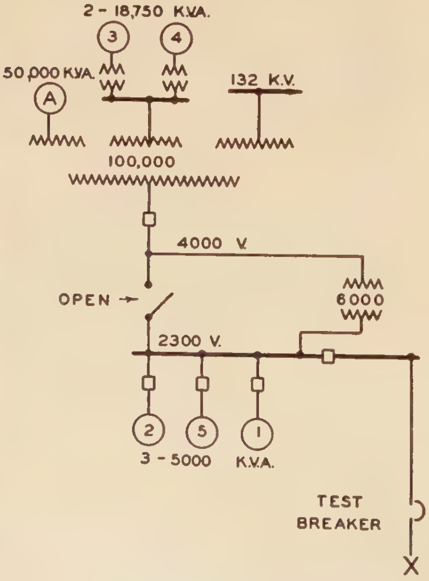

Figure 3. Special connections for 2,300-volt tests at Logan

The tests on one of these breakers at the Logan plant demonstrated very satisfactory performance. I shall attempt to describe these tests briefly with the aid of a few illustrations.

Figure 1 shows one of the 2,300-volt 1,200-ampere air circuit breakers set up in the yard at the Logan plant for the short-circuit tests. With the capacity that could be made available at the plant without interfering with the plant operation, it was not possible to obtain the full breaker rating of 125,000 kva, but by means of a special connection in which a 6,000-kva auxiliary bank was reversed from its normal direction of transformation, we were able to obtain more than 100,000 kva. The normal method of connecting this bank is shown in figure 2 from which you will note that the three 5,000-kva generators are operated at 4,000 volts in parallel with one of the windings of the large 100,000-kva bank, and with the 6,000-kva bank stepping down from 4,000 volts to 2,300. As this set-up gave a calculated short circuit of around 60,000 kva or only half of the rating of the breaker, it was decided to change the connection to that shown in figure 3 in which the three 5,000-kva generators were connected in parallel with the 2,300-volt side of bank 15 instead of the 4,000-volt bus. Although the generators operated at reduced excitation, this set-up provided a much greater short-circuit current than could be obtained in any other manner at 2,300 volts.

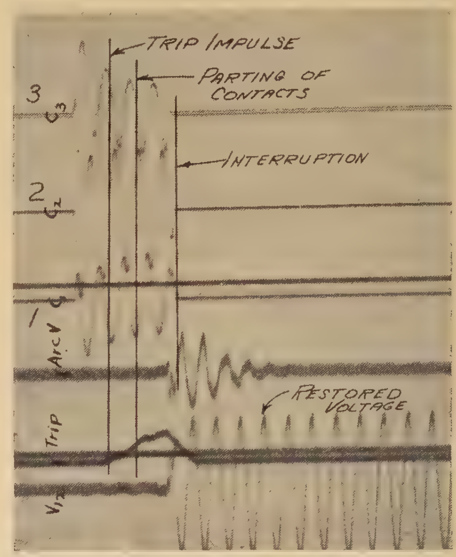

Figure 4. Oscillogram of test number 14 interrupting 22,800 amperes at 2,300 volts in three cycles

Altogether 25 shots were made on this breaker, with short-circuit current varying from approximately 3,000 amperes to a maximum of 22,800 amperes, and with voltages from 2,300 to above 4,000 volts. While time is not available to describe these tests in detail, a fairly complete record of the tests is shown in table I. You will note that, with the set-up in which the three 5,000-kva generators were connected in parallel with the 6,000-kva bank, a maximum recorded total root-mean-square current of 22,800 amperes was obtained on test 14. In order to overcome as far as

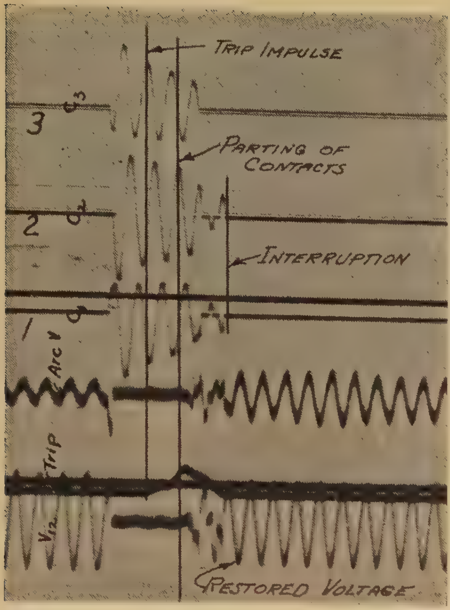

Figure 5. Oscillogram of test number 23 interrupting 15,200 amperes at 4,500 volts in 3.75 cycles

possible the effect of reduced excitation on the value of short-circuit current, the three generators operating in parallel with the system through the 6,000 bank were loaded with reactive kilovolt-amperes up to more than half of their respective ratings by increasing the field excitation.

You will also note from table I that the circuit breaker time, that is, the time in cycles measured from the trip impulse to the actual interruption of the arc, averaged approximately four cycles or less, throughout, with the exception of a single test of 6$^3/_4$ cycles in the third group. The extra long time in this case was undoubtedly due to an *overloaded trip mechanism.* On test number 10 immediately preceding this shot, the breaker failed to trip, entirely from this cause; while on the next shot, which was taken without making any adjustments, tripping occurred but was considerably delayed, as shown by the longer time on the oscillogram. At this point in the program the tripping mechanism was adjusted to relieve the excessive strain and, thereafter, normal tripping time was obtained throughout the remainder of the tests.

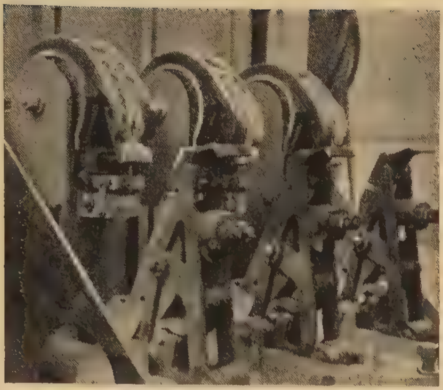

Figure 6. Contacts of ITE 2,300-volt air circuit breaker after short-circuit tests

Having shown that the breaker gave satisfactory performance with the highest current that could be obtained at 2,300 volts, it was decided to test the breaker, using the three generators alone excited to 4,000 volts or above. The last two groups of tests from number 17 to number 23, inclusive, in table I represent these tests made at the higher voltage. The last two tests made at 4,300 volts gave a maximum total root-mean-square current of 16,000 amperes. It will be noted that the breaker time for all of the tests at the higher voltage was less than four cycles.

In all the tests at heavier current values, a flash was observed above the breaker at the time of interruption. That this was mainly light and not actual fire was fairly well demonstrated by a ball of cotton which was suspended above one of the arc chutes and which was not ignited until the final shot made at 4,300 volts.

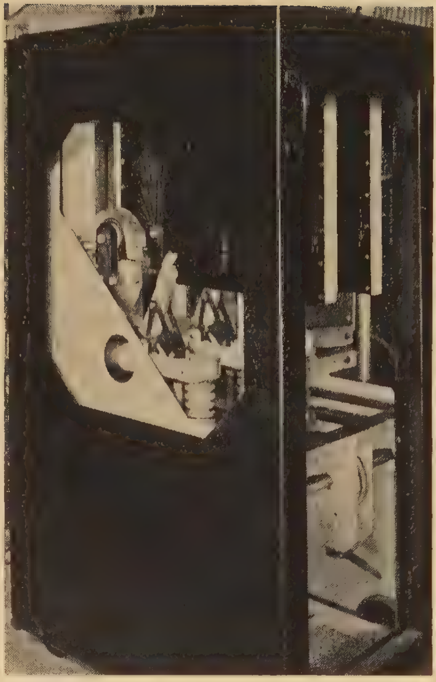

Figure 7. ITE 2,300-volt air circuit breaker with one arc chute removed

Figures 4 and 5 show typical oscillograms taken during these tests. Figure 4 represents test number 14 on which a current of 22,800 amperes at 2,300 volts was interrupted in three cycles. Figure 5 shows test number 23 on which a current of 15,200 amperes was interrupted in 3.75 cycles.

Twice during the tests the arc chutes were removed and contacts examined. Each time, a moderate amount of dressing of the main contacts was done before proceeding with additional tests, but the arcing con-

Table I. Short Circuit Tests at Logan on ITE 2,300-Volt Air Circuit Breaker

Test Number	Type	Generators	Bank No. 15 6,000 Kva	Volts	Initial Current in Arc			Breaker Time (Cycles)			Equivalent Kilovolt-amperes Interrupted
					1	2	3	1	2	3	
1	O	1	Open	2,300	2,850	3,080	3,130	4.0	4.0	4.25	12,500
2	CO	1	Open	2,300	3,340	3,910	3,180	3.25	3.25	3.25	15,500
3	O	2	Open	2,300	4,300	4,910	5,080	4.0	4.0	4.25	20,000
4	CO	2	Open	2,300	6,450	1,750	5,150	2.75	2.75	2.75	28,500
5	O	None	Closed	2,390	12,400	13,300	13,500	3.75	4.0	4.0	56,000
6	O	None	Closed	No Record							
7	CO	None	Closed	2,390	9,650	12,300	11,800	2.75	2.25	2.25	51,000
8	CO	None	Closed	2,390	12,300	12,500	12,900	2.75	2.75	2.75	53,000
9	O	2	Closed	2,430	15,600	17,000	18,000	4.0	4.0	4.0	75,000
9*A*	O	2	Closed	2,470	18,200	15,200	12,900	4.0	3.75	3.75	75,000
10	O	2	Closed	No Record							
10*A*	O	2	Closed	2,430	13,500	16,500	16,800	6.25	6.75	6.25	70,000
11	CO	2	Closed	No Record							
12	CO	2	Closed	2,470	13,900	14,500	16,800	2.25	2.25	2.0	70,000
13	O	3	Closed	2,570	20,900	19,200	17,400	3.0	3.0	3.0	93,000
14	O	3	Closed	2,560	17,700	22,800	16,300	3.0	3.0	2.75	101,000
15	CO	3	Closed	No Record							
16	CO	3	Closed	2,640	16,100	22,300	17,400	2.25	2.25	2.25	99,000
17	CO	1	Open	4,000	5,900	5,920	5,460	2.75	2.75	2.75	41,000
18	O	2	Open	4,000	9,650	7,600	6,500	3.5	3.5	3.5	67,000
19	CO	2	Open	4,000	5,360	9,400	8,000	2.25	2.25	2.25	65,000
20	O	3	Open	4,000	12,850	12,200	7,850	3.25	3.25	3.25	89,000
21	CO	3	Open	4,000	10,200	13,400	10,100	2.0	2.0	2.25	93,000
22	O	3	Open	4,300	16,100	13,900	9,500	3.75	3.75	3.75	111,000
23	CO	3	Open	4,300	14,100	15,200	13,500	3.25	3.75	2.25	105,000

tacts were not touched, and the amount of burning on these contacts was considered very small. The appearance of these contacts after the heavy current shots and prior to dressing is shown in figure 6.

Figures 7 and 8 are included to give a better idea of the appearance of this breaker. Figure 7 shows the breaker with one arc chute removed, while figure 8 shows a group of these breakers as they would appear assembled for service.

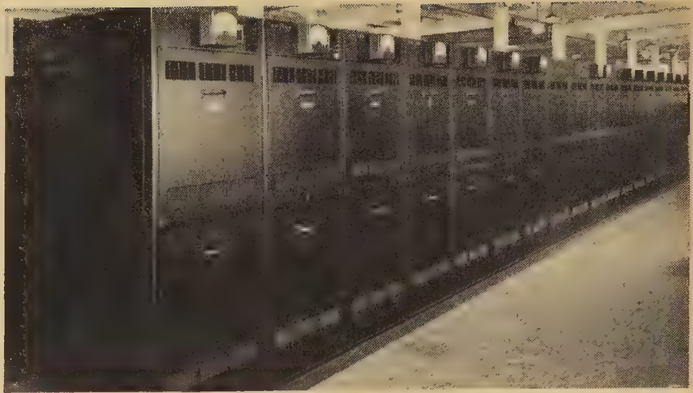

Figure 8. Assembled group of ITE 2,300-volt air circuit breakers

J. R. North (The Commonwealth and Southern Corporation, Jackson, Mich.): Keen interest is being shown throughout the industry in low-voltage indoor oilless circuit breakers, particularly for station auxiliary service at 2,400 volts in large generating stations. The "De-ion" air circuit breakers described by Mr. Dickinson would seem to have considerable possibility for such applications and should be very easy to inspect and maintain.

However, for properly evaluating these air circuit breakers, we should like to inquire regarding some of the design features.

(*a*) What are the ventilation requirements from the standpoint of temperature rise and also from the standpoint of flame emission.

(*b*) What is the duty cycle upon which the interrupting capacity ratings are based and what, if any, de-rating factors need to be applied for various reclosing duty cycles.

(*c*) What is the insulation strength—60-cycle flashover, impulse flashover minimum clearance to ground, and striking distance.

(*d*) What is the five-second current-carrying rating of these breakers (root-mean square amperes), as compared with their interrupting current rating.

M. H. Hobbs (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The series of tests given in Mr. Dickinson's paper, particularly those showing repetitive duty, show that we now have a circuit breaker which is apparently the answer to the requirements for severe service on motor and feeder circuits for station auxiliaries. A number of these have already been manufactured for this application, extending to other types of duty the operating advantages of "De-ion" breakers, which have proved so outstanding on heavy steel mill locations during the past several years.

Mr. Dickinson mentioned that the De-ion breaker is readily adaptable for mounting in metal-clad switchgear assemblies. This fact is more important now than ever before as the large majority of indoor switchgear is now this type, not only for station auxiliaries but for other general applications. It is equally important that all of the advantages of the designs of metal-clad switchgear for oil circuit breakers acquired during the years of its development should be retained in the structure for the De-ion breaker. Figures 11 and 12 show the two comparative structures, for oil and De-ion breakers respectively, and indicate comparative dimensions. It will be noted that the De-ion breaker is arranged as a horizontal draw-out unit as contrasted with the vertical draw-out arrangement for the oil breaker. This works out more satisfactorily for the circuit breaker design on account of the horizontal position of the arcing chamber and presents no handicaps as far as the switchgear is concerned. It would be just as illogical to use the vertical arrangement for this breaker as it was to use the horizontol for oil breakers having vertical stubs.

As noted from the two figures, the width and depth dimensions are identical, and the height of the De-ion unit is six inches more than the corresponding oil breaker unit. It would be possible to reduce the height except for the fact that space must be provided in the rear for potheads or similar cable terminating facilities. Accommodations for instrument panels are equivalent in that they can be mounted either in the front or rear, depending upon space facilities, that is whether only a single aisle or aisles front and rear are available.

Of course, no provision is necessary for circuit breaker gas exhaust as in the case of the oil breaker unit, although a small amount of ventilation is incorporated to assist in the small amount of gas dissipation which does occur. Porcelain is used for supporting the primary contacts, and completely insulated connections and busses are used in the housing. It is desirable to provide complete isolation of the secondary wiring from the primary compartment, and this is also provided for. Provision is made for automatic secondary contacts and for operation of the circuit breaker in the test position by means of a jumper. The usual interlocks insure that contact will not be broken on the disconnecting devices unless the circuit breaker is in the open position.

The availability of this breaker therefore enables us to have a complete switchgear unit, including bus, disconnecting devices, and instrument transformers, without the use of oil or compound in any of the compartments.

R. C. Dickinson: It is very pleasing to hear of the favor with which the 15-kv and 5-kv "De-ion" air breakers are regarded by the Philadelphia Electric Company as reported by Mr. Adams. This is typical of the high type of performance given by these breakers.

As Mr. Adams says, the non-oil type breaker has a field of its own regardless of the present state of oil breaker development. As pointed out in this paper, the widest field for the De-ion breaker, in general, has been where more frequent operation, either on overload or switching, is involved. The absence of oil deterioration and the long life of the contacts and interrupting element make this type of application most logical. However, since the De-ion air breakers are generally equipped with standard operating solenoids and interrupt the complete range of currents within their rating, they are suitable for any application where oil breakers might be applied.

In answer to a question raised by Mr. North, the De-ion air breaker is rated on the basis of the standard AIEE interrupting duty cycle and equivalent oil breaker de-rating factors are used for various reclosing duty-cycles. The De-ion breaker may be expected to require considerably less maintenance for the same duty than the ordinary oil circuit breaker.

In regard to continuous ratings, these breakers are at present supplied up to 2,000 amperes, and higher ratings will be built as occasion demands. As to higher interrupting ratings, the present ratings do not parallel oil breaker ratings in the higher kilovolt-ampere brackets. It is to be hoped that development efforts will eventually result in ratings equivalent to the higher capacity oil circuit breakers.

As to ventilation requirements, as Mr. Hobbs states in his discussion, a small amount is desirable for the dissipation of such gas as may be incident to circuit interruption but it is also desirable to assist in cooling the current carrying parts and reduce the possibility of moisture condensation on solid insulation surfaces. A small opening at the bottom of the cell door and one or two openings at the top of the cell are sufficient. The upper openings may be made drip-proof. There is no appreciable pressure built up within the cell and the gases are dissipated quite readily. Since the arc is ruptured in a completely enclosed chute, it will be obvious that no large amount of gas is set free in the cell as would be the case in an open magnetic chute construction. Years of service have indicated that the gases expelled from the breaker have caused no interference with operation nor undue maintenance. In fact, the maintenance on these breakers has been reported as unusually low.

We appreciate keenly Mr. Sporn's remarks and his interest in air circuit breakers. The new De-ion air circuit breaker has performed well on tests and over ten years of field experience on larger breakers of higher kilovolt-ampere rating, on which numerous field tests were made, indicates that these breakers will perform well in service. It is to be noted that single-phase interrupting tests were referred to in the paper. We value these tests quite highly since in most instances the actual restored voltage on the single-pole unit was as much or greater than the line-to-line

Enclosed Low-Voltage "De-ion" Air Circuit Breaker of High Interrupting Capacity

By JEROME SANDIN
ASSOCIATE AIEE

Synopsis: The demand for protection against fault currents up to 20,000 amperes at 250 volts d-c or 600 volts a-c has led to the development of air circuit breakers having the desirable features of the present line of enclosed air circuit breakers, but having higher interrupting capacity. Tests at 20,000 amperes on the circuit breaker of lower interrupting capacity showed that certain modifications were necessary. By increasing the gap between the contacts, by using contacts which resist welding, and by using a modified arc chamber and contact construction, it was found possible to make the breaker satisfactory for 20,000-ampere short circuits.

Introduction

An INTERESTING type of enclosed "De-ion" circuit breaker was developed some years ago to meet the demands of industry for a protective device with desirable characteristics such as:

1. Small size to permit the construction of safe, compact, and efficient panel boards, switchboard, and separate enclosures.
2. Sufficient capacity to be operated repeatedly without delay in a satisfactory manner under any condition to which it may be normally subjected.
3. Time delay to permit temporary overloads and instantaneous trip to remove short circuits instantly.
4. Sufficient interrupting capacity.
5. Safe to operate and free from fire hazard.
6. Nontamperable.
7. Easy to install and operate.
8. Low in cost.

This type of circuit breaker is made in frame sizes ranging from 50 to 600 amperes at voltages up to 250 volts d-c and 600 volts a-c and has a rupturing capacity of 10,000 amperes. This construction includes a molded insulated housing, De-ion arc chambers, an operating mechanism, a removable automatic trip unit, an insulated operating handle, and end terminals.

At the time these breakers were developed, 10,000-ampere interrupting capacity was considered ample to handle almost all of the industrial lighting and power circuits of 250 volts d-c or 600 volts a-c. Since then, however, industry has been using increasingly larger blocks of electrical energy, thus making it more and more necessary to have similar compact circuit breakers to handle short circuits of greater capacity. In order to meet this demand, the largest of these available breakers, namely the 600-ampere frame size was chosen for test and modification. A short-circuit interrupting capacity of 20,000 amperes at both 250 volts d-c and 600 volts a-c was set as the goal for this development.

The circuit breaker of higher interrupting capacity is intended for installation in switchboards or separate steel boxes, and for the protection of lighting and power circuits of large buildings or industrial plants where fault currents up to 20,000 amperes must be opened.

The original small size of the breaker was retained during the development. This was important since the size of the switchboards or the building space that must be set aside for them need not be increased. Further, most of the details of the breakers of the 10,000- and 20,000-ampere interrupting capacity are interchangeable which from a manufacturing and cost standpoint is very desirable.

Limitations of the Original Circuit Breaker

The 600-ampere circuit breaker of 10,000-ampere capacity is provided with silver main and secondary contacts, silver-tungsten (30 and 70 per cent proportion) arc contacts and arc chambers of the radial field type which is described in detail under the subtitle "Arc Chambers." Externally, both the original breaker and the finally developed breaker of high interrupting capacity, are alike. Figure 1 illustrates either of them. Figure 2 is typical of this type of breaker construction.

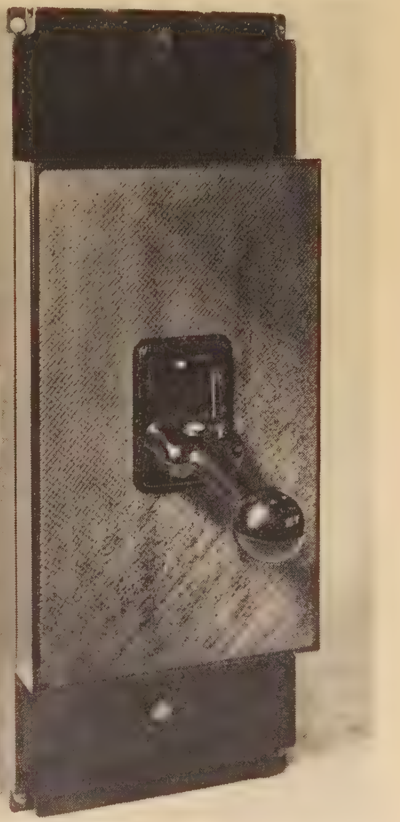

Figure 1. Two- or three-pole, 600-ampere circuit breaker of either 10,000- or 20,000-ampere interrupting capacity

Tests on the original circuit breaker at

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JEROME SANDIN is associated with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. Acknowledgment is made to Mr. L. R. Ludwig, Mr. G. G. Grissinger, and Mr. B. P Baker for their valuable contributions to this development. Much credit should go to Mr. B. P. Baker for carrying out the initial part of the development, and to Mr. L. R. Ludwig for his very material assistance in the preparation of the paper.

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voltage rating of the three-pole breaker. On many tests the generator was excited to more than 3,000 volts open circuit, single phase, on the 2,500-volt breaker and to 6,000 volts on the 5,000-volt breaker.

Replying to Mr. North's questions regarding insulation and current-carrying capacity without getting into the commercial ratings of these breakers, we can merely state that this class of breakers for 2,500- and 5,000-volt service are insulated to meet the AIEE requirements for 7,500-volt service and their short time ratings are compatible with their interrupting ratings at rated voltage.

In closing, I wish to thank all those who have entered into this discussion for their interest and favorable remarks.

20,000 amperes showed three limitations namely:

1. The arc frequently re-established between the moving and stationary contacts after it had traveled into the arc chamber away from the contacts, indicating that the distance between the contacts was too small.

2. The silver main contacts of both stationary and moving members welded together occasionally when short circuited with the breaker initially closed, but they welded almost always when the breaker was closed on the short circuits.

3. The arc chambers were of insufficient size to effectively vent and deionize the increased volume of ionized gas.

Theories, Modifications, and Improvements

Contact Separation

A greater gap between the contacts in the open position is required on higher short-circuit currents because of the presence of a greater amount of ionized gas between the contacts when 20,000 amperes is being interrupted.

Increased distance between the arc contacts allows the use of a larger number of plates in the arc chamber, increases the resistance of the arc, increases the discharge of ions to the plates if a larger number are used, and increases the neutralization of the ions by recombination, all of which facilitates the deionization of the gas.

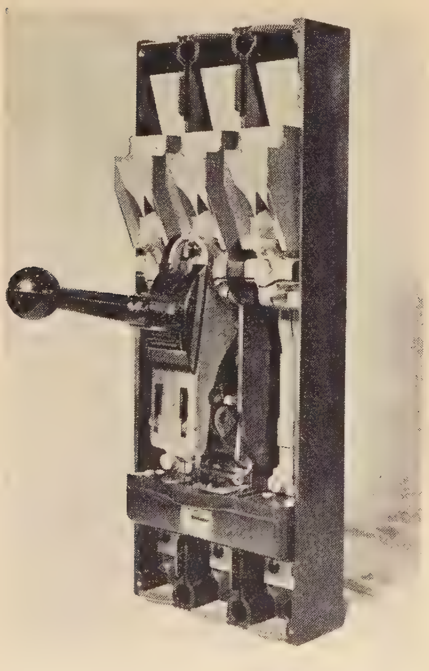


Figure 2. Three-pole, 600-ampere circuit breaker with cover removed, of 20,000-ampere interrupting capacity. Final construction

The separation between the arc contacts was increased from $^{13}/_{16}$ inch to $1\,^{1}/_{8}$ inches, or about 40 per cent. Tests up to about 36,000 amperes proved that this spacing was adequate.

Contacts

Silver contacts are very acceptable for current-carrying purposes since they show only a relatively small increase in contact drop after continuous duty. However, they weld together easily when subjected to high currents because of either high contact drop caused by the lessening of the contact pressure by magnetic forces, or by premature parting of the contacts before the mechanism is released by the trip unit and latch. To offset the effect of these magnetic forces it is necessary to increase the contact pressure by mechanical means or to provide a curved flexible conductor which will exert magnetic forces in such a direction as to cause increased contact pressure with increased current. If welding cannot be wholly eliminated in these ways, it is necessary to use another contact metal which is more resistant to welding.

The first modifications to the breaker included greater contact pressure and a change of the contacts from silver against silver to silver against silver-tungsten of 60 and 40 per cent proportion, to prevent the welding together of the contacts. This combination was tested at 20,000 amperes. The main contacts did not weld together when the short circuits were thrown on the breaker in the closed position, but welding occurred in about half of the tests when the breaker was closed on the short circuits.

Silver tungsten normally increases the contact drop but this was partially offset by increasing the contact pressure. The contact drop remained approximately the same for the first four short circuits and then began increasing rapidly due to the burning of the contact material.

A change in the main contacts from silver against silver-tungsten to silver-tungsten against silver-tungsten of 60 and 40 per cent proportion was tried. This combination did not entirely eliminate the possibility of welding when the breaker was closed on 20,000-ampere short circuits but the percentage was reduced.

Main contacts made of silver-molybdenum were tried in order to overcome the contact welding problem. The tests were highly satisfactory from this standpoint, for at no time did these contacts weld together on short circuit. The contact drop remained approximately the same throughout the tests. These contacts also showed considerably less signs of burning away than did the silver-tungsten contacts. However, silver-molybdenum contacts were found to have a very decided drawback. The drop across these contacts increased appreciably in a few days due to the oxidation of the molybdenum. A number of breakers without current were exposed to an ordinary atmosphere from one to three weeks, and they were tested for contact drop from time to time. Some of these breakers were in closed position and others were in open position. The drop readings across these breakers were initially between 12 and 18 millivolts at 250 amperes d-c, and the final drop values varied anywhere from 30 to 150 millivolts depending on the length of exposure. A breaker having a drop of about 50 millivolts was tested with full-load current for about 48 hours continuously, but strangely there was no increase in contact drop during this time. It was decided to abandon the use of silver-molybdenum because of the appreciable increase in contact loss under ordinary atmospheric conditions.

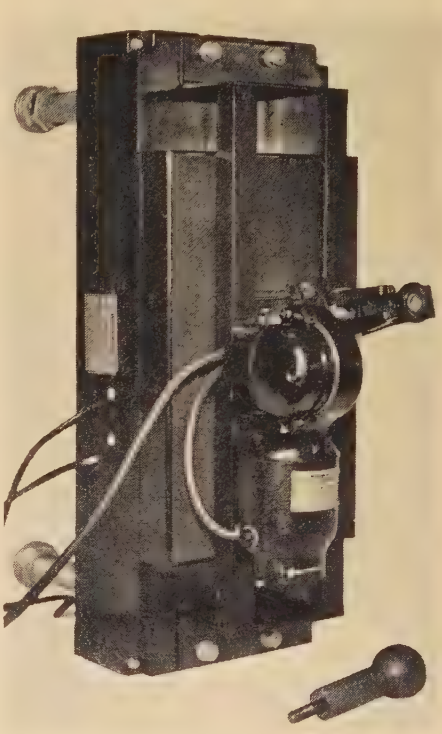


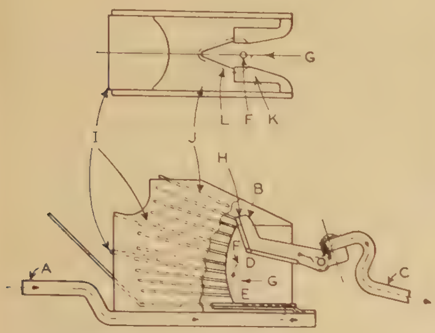
Figure 3. Two- or three-pole, 600-ampere circuit breaker of either 10,000- or 20,000-ampere interrupting capacity with motor mechanism for electrical operation

A contact construction was finally produced which included the following changes:

1. Silver-tungsten contacts of 30 and 70 per

cent proportion for all moving and stationary members to positively prevent welding at 20,000 amperes or more, with either close-open or open-close-open breaker operation. The use of this alloy reduces the burning of the contact material to a minimum.

2. Center contact members of the roll type which make contact at the heel or farthest point from the arc chamber when the breaker is closed and which roll to the toe or into the slot of the arc chamber while the breaker is opening. This center contact takes the place of the secondary and arc contacts of the old construction which derived their pressure from one spring. All of this spring pressure is now used for the one center contact thus giving less contact drop.



A—STATIONARY CONTACT MEMBER
B—MOVING CONTACT MEMBER
C—FLEXIBLE CONDUCTOR
D,E,AND F—FLUX AT D AND E TEND TO FORCE ARC F IN DIRECTION G
H—ARC HORN FACED WITH SILVER-TUNGSTEN TO REDUCE BURNING
J—STEEL PLATES
K—ARC SHIELDS
F,G,AND L—FLUX L PULLS ARC F IN DIRECTION G

Figure 4. Schematic diagram of stationary and moving arc contacts and arc chamber

3. An arcing horn at the end of the center moving contact, to elongate the arc and to more positively insure that the arc strikes all of the plates in the arc chamber. Facing the arcing horn with silver-tungsten (30 and 70 per cent) reduced the burning of the horn considerably and thereby lessened the amount of gas.

4. Moving and stationary contact members, consisting of two outside main contacts and one center arc contact, having a definite contact opening and closing sequence to reduce the burning of the contact material and to positively insure the formation of the arc between the arc contacts and not between the main contacts. This contact sequence consists of the right-hand main contact parting ahead of the left-hand main contact which is followed by the parting of the arc contacts. Since the drop is approximately the same across each of these contacts, the resistance does not rise too rapidly when the contacts are parting.

5. The direction of the flow of current through the stationary conductor to the center contact was changed to assist forcing the arc into the arc chamber. The change in current direction produces a flux condition which exerts a force on the arc in the proper direction, as shown in figure 4. The old construction produced flux, which tended to force the arc at one end away from the arc chamber.

Short-circuit tests on breakers having these modifications show that contact welding has been entirely eliminated, that contact burning has been considerably reduced, that there is less outward disturbance, and that the rupturing capacity of the breaker has been considerably increased.

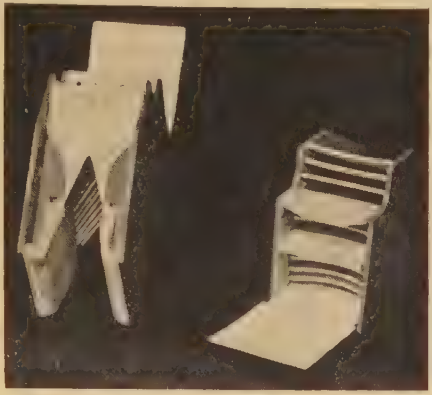


Figure 5. Arc chamber of 20,000-ampere interrupting capacity

Arc Chamber

The arc chamber used during the early stages of this development is of the cold-cathode type which has a radial field for the purpose of spinning the arc to keep the electrodes cool.

This arc chamber consists essentially of a series of copper plates, each fitted into and surrounded by a steel plate except for a V-shaped opening through which the arc contacts move. These plate assemblies are stacked one upon the other and insulated from each other by fiber. A flat coil is located at the center of the stack of plates and is connected to the two adjacent copper plates so that it is in series with the line after the arc is broken into a series of small arcs between the copper plates. The flat coil has a center steel core and produces a radial field from the core to the surrounding steel plates.

In addition there is a one-turn coil which is connected to the stationary arc contact and to the line terminal so that the arc contacts and the coil are in series when the main contacts part. This coil energizes the iron surrounding the copper plates and causes the arc to be moved from its point of inception up into the narrow part of the V plates. From this point the arcs are under the influence of the radial field and are moved with a high velocity in an annular path formed by the insulation between the copper plates.

When alternating current is being interrupted, these series arcs continue to rotate until the current reaches its natural zero value. The d-c arc is extinguished as soon as the current is reduced to zero, which depends on the inductance of the circuit and the amount the arc voltage exceeds the line voltage.

The arc chamber as described above was enlarged by increasing the number of copper plates from nine to 12 in order to take care of the heavier short-circuit currents. These additional plates increase the plate area which helps to cool the hot gases and assist the process of deionization. Since the spacing between the plates remains unchanged, the additional plates will permit increased venting which will help to increase the interrupting capacity.

The enlarged arc chamber was short-circuited at 20,000 amperes on both 250 volts d-c and 600 volts a-c. It interrupted all of the short circuits it was subjected to.

It was thought that by use of the plain-plate type of arc chamber, as shown by figure 5, the following advantages could be obtained at the higher short-circuit value.

1. Better insulation between the line and load sides of the breaker in open position because of the elimination of the shunt which connects the top plate of the arc chamber of the radial field type to the load side of the breaker.
2. Increased venting of the arc gases.
3. Simpler construction.
4. Better performance on direct current.

The arc chamber of this plain-plate type consists of a series of V-slotted steel plates mounted between insulated supports, and it is so placed that the slots of the steel plates extend over the arc contacts. The moving arc contact must pass through the slotted steel plates as it leaves the stationary arc contact. As this action takes place, the arc formed is magnetically driven into the steel plates and is usually broken into a series of short arcs, depending on the amount of current and whether the current is alternating or direct.

The tests on the plain-plate type of arc chamber indicated increased venting, resulting in less back pressure and less burning of the contacts, better insulation between the line and load side of the breaker, more satisfactory performance on direct current, and less heating of the arc chamber which permits less interval of time between short circuits. As a result of these tests, the plain-plate type of arc chamber was adopted for the heavy-duty breakers.

Tests on this arc chamber also indicated that an arc produced by small a-c short-circuit currents usually does not transfer to the steel plates and form short series arcs, but an arc produced by heavier a-c short-circuit currents or not too low d-c currents usually would transfer to the steel plates and form the short series arcs. The degree of venting at the top end of the steel plates determines largely whether or not the arc transfers to the steel plates. Free venting encourages arc transfer.

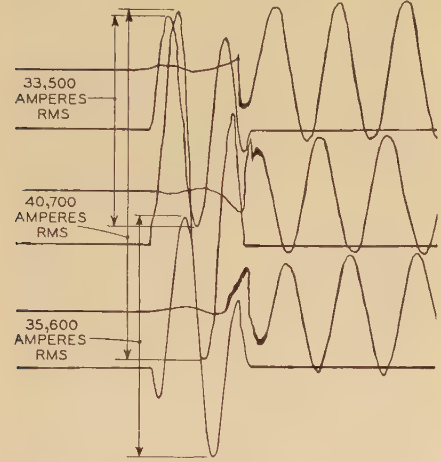


Figure 6. Oscillogram showing a three-phase interruption at 36,000 amperes, 600 volts, 60 cycles

Deionization of the arc is effected either by the ions neutralizing their charges among themselves or by discharging into the electrodes. The current and voltage a given device can interrupt depends on the length of the arc, the material and size of the electrodes, the proximity of the walls or plates to the arc, the degree of venting, and number of series arcs which determine the number of positive-ion-spaced-charge sheaths in front of the cathode. Those who wish to learn of the fundamentals of arc phenomena should refer to previous articles[2–5] which treat this subject very thoroughly.

When alternating current is being interrupted, the arc or the series arcs continue until the current reaches its natural zero value. At this time the processes of deionization transform the conducting ionized gas into an insulating gas. This prevents the arc from re-establishing by preventing the line voltage from building up current in the opposite direction. The a-c arc is extinguished at the end of the first half cycle.

The arc motion is the same for alternating and direct current, although the effect on the circuit and the way the arc is extinguished is quite different. For a given line voltage a much larger number of plates and much larger gap between the arc contacts must be used for direct current so that the total arc voltage is greater than the line voltage. This difference between the arc voltage and the line voltage is necessary to cause the current to decrease to zero.

Arc shields line both sides of the arc chamber to prevent the arc from burning or striking the lower sides of the steel plates. The burning of unprotected sides of steel plates tends to cause an excess of gas. The striking of the unprotected sides by the arc occurs mainly on low d-c currents, and hinders the arc from rising to the end of the slot, thus causing prolonged arcing.

The arc splitters are spaced to form three compartments directly above the steel plates of each arc chamber to prevent reignition of the arc gas as it is vented from the plates.

Table I. Contact-Drop Data Taken After Short-Circuit Tests

Amperes at 600 Volts, 60 Cycles, 3 Phase	Test Cycles	Millivolts Drop at 250 Amperes D-C		
		Left Pole	Center Pole	Right Pole
		*7.4	*7.8	*6.8
20,000	*O*			
20,000	*CO*	6.5	5.5	5.4
20,000	*O*			
20,000	*CO*	7.5	7.2	6.5
20,000	*O*			
20,000	*CO*	6.2	6.6	7.1
32,000	*O*			
32,000	*CO*	18.2	9.8	13.5

* Initial drop readings

The arc formed between the arc contacts is acted upon by two forces, which tend to draw it away from the contacts into the steel plates of the arc chamber as shown by figure 4. They are namely: the flux at *D* and *E* which is created by the direction of flow of the current through the arc contacts, and the magnetic field produced in the steel plates.

Description of the Final Developed Circuit Breaker

The circuit breaker is built in an enclosed insulating housing of two parts known as the base and cover. The parts are made from "Moldarta" of a composition selected to give proper mechanical strength, resistance to such heat as it may be subjected, and to resist warping and the absorption of moisture. Both base and cover are provided with deep ribs or walls to permit close assembly of the different poles and to give adequate strength.

An operating handle made of Moldarta is provided to close, open, and reset the breakers. This handle moves in a shielded slot located near the center of the cover. Position indication is obtained from the operating handle. Upper position of the handle indicates the breaker is closed, lower position of the handle indicates the breaker is opened, and mid-position of the handle indicates automatic tripping.

Quick make and quick break are assured by means of an over-center spring toggle which prevents the possibility of slow closing. The breaker is trip-free from the handle at all times after the arc tips have made contact.

All triggers and latches are made of rust-resisting nitride steel. All bearings are made of noncorrosive metal.

Automatic overload tripping is obtained by means of a thermal release consisting of a heater, a bimetal part that changes its shape with change of temperature, and a trigger which is moved by the bimetal part to unlatch the breaker. Resulting time limits are sufficient to prevent interruptions due to overloads of short duration and still give full protection against heating.

Supplementing the thermal release, there is a one-turn electromagnet which trips the breaker instantaneously on currents ranging from six to eight times the normal current rating.

Both the thermal and magnetic releases are mounted on a base, together with a trip bar and trigger. This unit is called a trip unit and is made up in different current ratings. These trip units can be easily removed from the breaker, and are interchangeable which permits a change in current rating to be made after installation.

Figure 2 shows a final developed circuit breaker with the cover removed. Figure 3 shows a complete circuit breaker of either 10,000- or 20,000-ampere interrupting capacity with a motor mechanism for electrical operation.

The circuit breakers are rated at 70 to 600 amperes, 250 volts d-c or 600 volts a-c, two-pole, and 70 to 600 amperes, 600 volts a-c, three-pole. The breakers

Table II. Weight and Size Data

Connection	Weight (Pounds)	*Over-all Size		
		Width	Length	Depth
Front	53	$8^{1}/_{2}$	22	$5^{1}/_{2}$
Rear	62	$8^{1}/_{2}$	22	**$11^{1}/_{2}$

* Operating handle not included.
** Rear-connected terminals included.

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[2] For all numbered references, see list at end of paper.

as shown are for rear connection only. By adding a gas by-pass at the top front end of the cover, the breaker can be used for front connection. The gas by-pass assists the venting of the gas around the terminals. The same molded main base and cover are used for both the two- and three-pole breakers.

Since size was a very important factor in the development of this breaker, table II is given, listing the over-all size and weights of both the front- and rear-connected breaker units.

Final Test Results

Figure 6 illustrates the performance of the final breaker opening a short circuit at 36,000 amperes, 600 volts, 60 cycles, 3 phase. This particular breaker satisfactorily opened one open and CO short circuit at 20,000 amperes, one open and CO at 25,000 amperes, one open and CO at 26,000 amperes, and two open and CO short circuits at 36,000 amperes. The contacts and steel plates were burned but not excessively.

A similar breaker was tested to determine the effect of severe short circuits on the contact drop. Table I gives the short-circuit and contact-drop data. These data indicate that the contacts were still in excellent shape after six short circuits at 20,000 amperes. The increase in contact drop after the two 32,000 ampere short circuits is not enough to cause overheating or to affect the thermal trip calibrations.

Conclusion

The circuit breaker, as finally developed, is of a size which enables a compact and efficient switchboard construction, has a considerable safety margin over the 20,000-ampere rupturing capacity, and permits interchangeability of a large number of detail parts with the circuit breaker of the same normal rating but of 10,000 ampere rupturing capacity.

References

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5. Extinction of A-C Arcs in Turbulent Gases, T. E. Browne, Jr. Presented at the winter convention of the AIEE, New York, N. Y., January 25–29, 1932.

Line-Type Lightning Arrester Performance Data

THIS REPORT presents characteristics of line-type arresters rated 20 to 73 kv, and is a continuation of the previous subcommittee report on "Distribution Lightning Arrester Performance Data" published in the AIEE Transactions, volume 56, 1937, pages 576–7.

Data have been presented relating to the impulse characteristics of insulation both as used on lines and in stations. Data on the rates of voltage rise and current magnitude to be encountered by protective devices in the field are being accumulated rather slowly. In order to have a basis for comparing arrester characteristics, a standard test was set up which indicates the arrester protective characteristic which falls in the range of service conditions. While the test was empirically set up, the characteristics obtained can be compared with the insulation to show the margin of protection afforded.

The present standard requires an applied impulse voltage rising at the rate of 100 kv per microsecond per 11.5 kv of rating in these voltage classes. In effect this results in an impulse sparkover of the arrester series gap in about 0.4 microsecond after the impulse voltage begins to rise. After the arrester begins to discharge the impulse current should rise to 1,500 amperes in ten microseconds and fall to half value in ten more microseconds. This current results in a voltage drop or impedance drop across the characteristic element of the arrester. As the impedance drop varies somewhat with current, characteristics also are presented for currents of 3,000 amperes and 5,000 amperes.

The lightning-arrester manufacturers have furnished the data from which the average characteristic of available arresters are plotted and tabulated. Tolerances are given to include the expected

Table I. Line-Type Arrester Characteristics (20–73 Kv)

Arrester Rating (Kv)*		Gap Breakdown (Crest Kv)	Impedance Voltage; Crest Kv When Discharging Currents of		
			1500 Amperes	3000 Amperes	5000 Amperes
20	Max.	97	83	90	94
	Ave.	75	69	75	78
	Min.	52	55	60	63
25	Max.	118	104	112	118
	Ave.	95	87	94	98
	Min.	64	69	75	79
30	Max.	139	124	134	142
	Ave.	112	104	112	117
	Min.	78	83	89	94
37	Max.	169	155	168	176
	Ave.	135	129	140	146
	Min.	98	103	112	117
40	Max.	180	168	182	190
	Ave.	147	140	151	158
	Min.	104	112	121	127
50	Max.	225	210	228	238
	Ave.	180	175	188	198
	Min.	131	140	150	159
60	Max.	267	252	274	286
	Ave.	217	210	226	238
	Min.	157	168	182	190
73	Max.	323	309	333	348
	Ave.	265	258	278	290
	Min	195	206	222	232

Notes: Gap breakdown taken on rate of voltage rise of 100 kv per microsecond per 11.5 kv of rating. All test currents 10/20 wave. The 60-cycle sparkover potential of all arresters shown in this tabulation will not be less than 150 per cent of arrester rating.

* These ratings are maximum permissible line-to-ground root-mean-square voltages.

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Personnel of AIEE lightning arrester subcommittee: J. R. North, *chairman;* H. W. Collins, J. M. Flanigen, I. W. Gross, Herman Halperin, K. B. McEachron, J. R. McFarlin, A. M. Opsahl, A. H. Schirmer, H. K. Sels, L. G. Smith, H. R. Stewart, J. J. Torok, and H. L. Rorden.

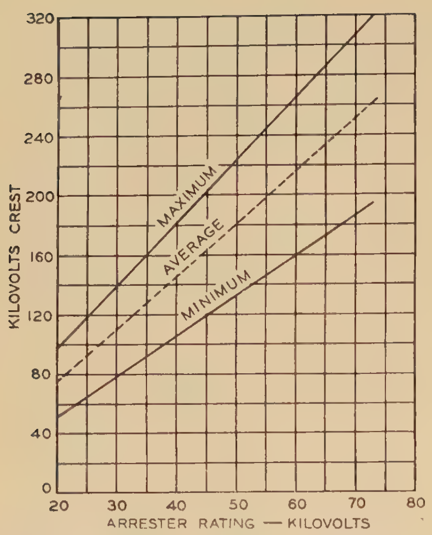

Figure 1. Impulse spark-over voltages, line-type arrester

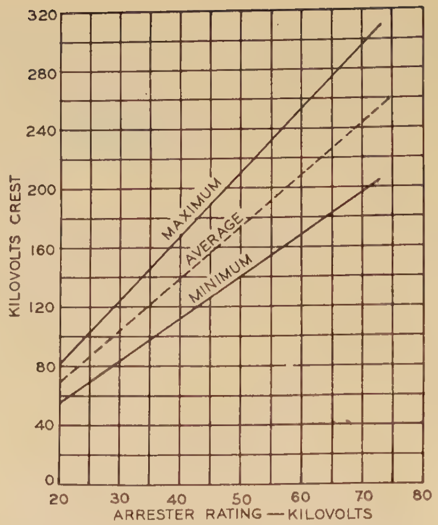

Figure 2. Impedance drop at 1,500 amperes, line-type arresters

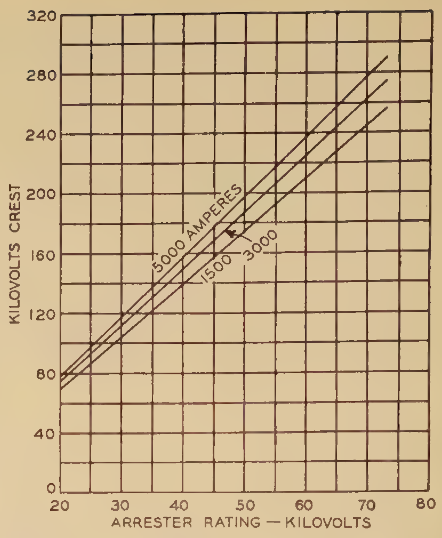

Figure 3. Average impedance drop, 1,500, 3,000, and 5,000 amperes, line-type arresters

variation from the average for the industry.

The over-all characteristic of the lightning arrester is usually given in the typical volt-time curve under specified conditions. The pertinent voltage magnitudes only are given here in order to simplify the data. By a comparison of the typical volt-time arrester characteristic with the volt-time characteristic of the insulation to be protected, a logical evaluation of the protection can be made.

Transactions

Papers and Discussions Comprising Pages 663–712 of the 1938 Volume

System Analysis for Petersen-Coil Application

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Synopsis: Careful analysis of the characteristics of a power system has been found to be necessary before applying Petersen coils to a system which has been operating either with the neutral isolated or grounded. In these two companion papers on Petersen coils, accent has been placed on the analysis of system characteristics in order to determine whether or not the application of Petersen coils will be satisfactory.

In this paper (part I) the general features of Petersen-coil application are considered, and the fundamentals of calculating coil characteristics are given. In the companion paper (part II) by F. Von Voigtlander, the methods of performing detailed calculations on system fault currents, coil ratings, and voltages are given in an illustrative example, together with field tests to check design computations and performance of the equipment.

Part I—Operating Features and Basic Calculations—By W. C. Champe

Introduction

CONSIDERABLE interest has recently been shown in this country in the application of resonant neutral grounding reactors, or Petersen coils, to medium- and high-voltage transmission systems for the purpose of extinguishing single line-to-ground faults without the operation of circuit breakers and before they spread to phase-to-phase or three-phase short circuits. Applications have been made of Petersen coils to existing systems, most of these having been systems which were originally operated with the neutral isolated, since adequate relaying of single line-to-ground faults is ordinarily more difficult to obtain on an isolated-neutral system than on a grounded-neutral system.

A Petersen coil usually consists of a tapped inductance with iron core, connected between ground and the neutral point of a suitable transformer bank so that, in the case of an arc to ground of one conductor of the transmission system, the total reactive lagging current from the coils will be approximately equal to the residual charging current to ground of the system. The inductive reactance of the system, most of which will be in the Petersen coil or coils, will then be approximately equal to the capacitive reactance of the two unfaulted conductors to ground. If the coils are properly tuned, the fault current in a single phase-to-ground fault will be principally the in-phase component, which cannot be balanced out by the coils and ordinarily will be so low that the arc will be self-extinguishing.

Effects on System Operation

Following is an outline of the effects on system operation to be expected from the installation of Petersen coils as compared to isolated-neutral and grounded-neutral systems:

GROUND-FAULT CURRENT MAGNITUDE

1. On most grounded-neutral systems in this country, the ground-fault currents are quite large.

2. On an isolated-neutral system, the current through a single line-to-ground fault depends upon the length of transmission lines, and with an extensive system is large enough to maintain an arc.

3. On Petersen-coil systems, when properly tuned, the ground-fault current is reduced to a relatively small value, approximately the in-phase component of residual current. Damage to the equipment at the point of fault, due to current, is therefore greatly reduced. More thorough consideration of current magnitudes is given in a later part of this paper.

GROUND-FAULT ELIMINATION

1. On grounded-neutral systems, all types of ground faults ordinarily cause trip-outs.

2. On all isolated-neutral systems, unless small in extent, single-phase faults to ground are not self-extinguishing. Since these faults are difficult to relay properly, they may continue until they become two-phase or three-phase faults and the section of line is relayed out.

3. On a system to which Petersen coils can be successfully applied, practically all transitory single-phase faults are self-extinguishing before developing into two-phase or three-phase faults. Relay operations and interruptions to service, therefore, should be much reduced by the installation of Petersen coils on either a grounded-neutral or isolated-neutral system.

MAXIMUM LINE-TO-GROUND VOLTAGES

1. Grounded-neutral systems in this country usually have sufficiently low values of neutral grounding resistance or reactance that the neutral at all parts of the system does not vary greatly from ground potential. Line-to-ground voltages on the unfaulted phases, therefore, do not increase greatly during fault conditions.

2. On isolated-neutral systems, line-to-ground voltages on the unfaulted phases at the point of fault are approximately equal to line-to-line voltages, and at distant points may be 20 to 50 per cent greater. In some cases, this may result in a double line-to-ground fault.

3. With one Petersen coil, overvoltages for faults at most locations would be lower than on an isolated-neutral system, and equipment would be less likely to be damaged, since the fault duration would be reduced. The installation of additional Petersen coils would reduce the overvoltages for faults at any location. Overvoltages are discussed in more detail in a later section.

LIGHTNING-ARRESTER RATING

1. On a system having the neutral effectively grounded, these ratings can generally be approximately 80 per cent of the maximum line-to-line voltage.

2. On an isolated-neutral system, these ratings must be at least equal to line-to-line voltage.

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W. C. CHAMPE is electrical engineer in the division of engineering and construction of the City of Toledo, Ohio, and F. VON VOIGTLANDER is employed in the technical section, electrical engineering department, Commonwealth and Southern Corporation, Jackson, Mich. These papers (parts I and II) are based on a study of Petersen-coil application and operation over a period of years, and the authors wish to express acknowledgment of the suggestions given by their associates, in particular to Mr. J. R. North for his encouragement and assistance.

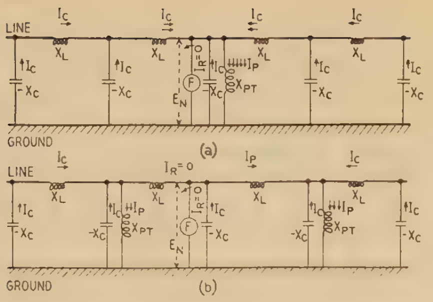

Figure 1. Zero-sequence network, showing effect of one Petersen coil (a) and two Petersen coils (b) on the distribution of fault current due to a single line-to-ground fault

X_L = Line series reactance
X_C = Line shunt capacitive reactance to ground
X_{PT} = Reactance of Petersen coil with associated transformer (per-phase value of transformer reactance X_{TR} plus three times the actual Petersen-coil reactance X_P)
X_{TR} = Reactance of transformer used with Petersen coil
X_P = Actual Petersen-coil reactance ($^1/_3$ the per-phase value)
I_C = Charging current to ground
I_P = Petersen-coil current
I_R = Residual current
F = Single line-to-ground fault
E_N = Volts, line to neutral

These zero-sequence quantities are the usual values, per phase, based on three conductors in parallel, except the Petersen-coil reactance, which is actual reactance. Actual currents at point of fault and in Petersen coils are three times the zero-sequence current

3. On a Petersen-coil system, these ratings cannot be appreciably lower than for an isolated-neutral system, provided only one Petersen coil is installed. With additional Petersen coils, it may be possible to reduce these ratings somewhat.

EFFECT ON COMMUNICATION FACILITIES

1. With a grounded-neutral system, the fundamental-frequency induced voltage resulting from single line-to-ground faults may be excessive.

2. On isolated-neutral systems, while the fundamental-frequency induction on all but very extensive systems is usually less than for grounded-neutral systems, noise-frequency induction may be severe due to the possibility of long-duration ground faults.

3. An installation of Petersen coils usually reduces the effects on communication facilities considerably, as the magnitudes of the current carried over the transmission lines during faults would in general be smaller. For certain fault and exposure locations, the residual current in an exposure may be almost zero. The number of locations at which the residual current would be small increases as the number of Petersen-coil installations on the system is increased. This is especially important upon the occurrence of a permanent fault, such as a conductor lying on the ground. The effect of additional coils in reducing line currents is shown in figure 1.

SHOCK TO THE SYSTEM

1. With a grounded-neutral system, a ground fault may result in a great shock due to the heavy current.

2. With an isolated-neutral system, a ground fault may result in a large voltage shock.

3. A properly designed Petersen-coil system results in very little shock to the system upon the occurrence of a ground fault.

The principal advantages of Petersen coils, therefore, are seen to be the clearing of most ground faults without the operation of circuit breakers or interruption to service, the reduction in damage at the point of fault and in effects on communication resulting from reduced fault currents, the reduced overvoltages as compared to an isolated-neutral system, and the reduced shock to the system caused by ground faults.

In considering the installation of Petersen coils, the following limitations of the coils should be kept firmly in mind:

1. They do not compensate for the in-phase component.

2. They do not entirely prevent system overvoltages to ground from exceeding normal phase-to-phase voltages, but only limit their extremes in magnitude and restrict their duration.

3. They require that all apparatus and equipment connected between line and ground be capable of sustaining overvoltages.

4. They have no effect on phase-to-phase faults as such.

5. They do not clear permanent ground faults, but help to mitigate their effect.

Each of the above factors must definitely be taken into account when considering Petersen coils in order to determine their efficacy.

Zero-Sequence Capacitive Reactance and Residual Charging Current to Ground

The first step in any calculations for applying Petersen coils is the determination of the zero-sequence capacitive reactance of a short line section with one conductor grounded, neglecting the effect of line series reactance. Methods of calculating this value on a per-phase-per-mile basis are given in several works.[3,6]

If the residual charging current to ground with one conductor grounded is first obtained by test or otherwise, it may be expressed on a per-mile basis. For later use in combining with other network reactances, the zero-sequence capacitive reactance to ground in ohms per phase should be obtained by dividing the volts to neutral by $^1/_3$ the charging current to ground in amperes. This charging current is the same as the charging current to ground from all three conductors connected in parallel and energized at line-to-neutral voltage. Roughly, its value for single-circuit lines of moderate or high voltage is 1.5 to 1.7 times the per-phase value of normal three-phase balanced charging current of the line. This value does not include any in-phase component or the effect of line series reactance.

Where double-circuit lines are involved, the value of residual charging current per mile per circuit must be reduced since the residual charging current to ground of one mile of double circuit line is considerably less than twice the value for one mile of single circuit line of equal spacing.

The capacitive reactance to ground is influenced by a number of factors such as the effect of: the supporting poles, substation structures, and trees and shrubbery along the right of way, and variation in sag, etc. Although the value can be calculated quite accurately, as shown in part II, it is usually advisable to check these calculations by test for any particular system if there is any question about the accuracy of the fundamental data.

A few transpositions may be necessary in the transmission lines to prevent a residual voltage of considerable proportions being maintained on the system during normal conditions, with a consequent flow of current through the Petersen coil.

In-Phase Component of Fault Current

Petersen coils do not balance out the in-phase component of current in the arc caused by losses, such as corona loss, leakage over insulators, unbalanced copper losses, and Petersen coil losses, nor do they balance out the harmonic currents in the arc. The in-phase component must be carefully checked to make sure that it will not be large enough to maintain the arc readily and prevent extinction by the Petersen coils. Fortunately, the arc will be self-extinguishing with a larger magnitude of in-phase component than of quadrature component of current, as the current and voltage will

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[3] For all numbered references, see list at end of paper.

both go through zero at the same instant.

The in-phase component varies considerably with weather conditions and is difficult to calculate accurately. Unless preliminary consideration shows that the value is small, it is desirable that tests be made on a power system to determine the magnitude of the in-phase component before Petersen coils are applied. It is also important to keep in mind that the magnitude of this component is generally reduced as the number of Petersen coils on the system is increased, as the current through the lines and the voltage distortion over the system would be reduced. An example of the magnitude of this component is shown in part II.

Methods of compensating for the in-phase component have been developed, but the complications involved tend to make their use undesirable.

System Voltages and Effect on Currents

On an isolated-neutral system the voltages at the point of fault are displaced so that ground is at one corner of the voltage triangle, the delta (line-to line) voltages remaining approximately unchanged in magnitude. As locations distant from the point of fault are considered, the voltage triangle shifts further away from ground due to the effect of charging and in-phase components of current being drawn over the series impedance of the line. The result is that voltage appears on the faulted conductor (voltage *Z'G* of figure 2*c*), and the voltage of the conductor ahead of the faulted conductor in time sequence has a voltage to ground greater than the normal line-to-line value (voltage *Y'G*). If the transmission system is at all extensive, the effect of the series impedance is much more important than usually thought and may easily impress a voltage between an unfaulted phase and ground of 120 to 150 per cent of normal line-to-line voltage. In extreme cases, a condition of resonance between capacitive reactance to ground and series reactance of the line may be obtained with one conductor grounded.

The effect of series reactance is especially important if a long section of small-conductor line connects two capacitance centers of the system.

The reactance of a Petersen coil is not of a sufficiently low value to hold the neutral of the associated transformer at ground potential during a ground fault, and the system voltages are displaced to a condition approximating that on an isolated neutral system. If there is only one Petersen coil on the system and the fault is near the coil, voltage and current conditions on the lines will be approximately the same as on an isolated-neutral system. This results in an increase in the total charging current and, therefore, increases the capacity required in a Petersen coil. These effects can be reduced, however, by the installation of additional coils, as the charging current for any section of the system can then be balanced out by a nearby coil and large currents will not have to be drawn over the line impedance.

On some systems, particularly those with small conductors and high voltages or at high altitudes, the increase in corona current due to the increase in voltage at points distant from the ground fault may be an important factor in preventing the successful operation of the coil.

Number of Coils Required

As the fault location is moved in from the ends of the system toward a Petersen coil, the lagging current through the Petersen coil will increase appreciably; also the charging current of the system. If the Petersen coils are in tune for a fault at any one location on the system, they will be in tune for a fault at any other location, provided the system itself does not change by having lines switched on or off. This applies regardless of whether there is only one Petersen coil or several. As regards the number of grounding points, this is different than the application of grounding banks on grounded neutral systems, since then it may be necessary to place the banks close enough together to give adequate current for relays, and more than one bank is almost always required for directional selectivity.

If the scheme is used of short-circuiting the coils in case the fault should continue for an appreciable length of time, and tripping the faulted line out by ground relays, then at least two Petersen coils are frequently desirable.

Two or more Petersen coils may also be desirable for other reasons. In case the transmission system is likely to be split so that sections would otherwise be without a Petersen coil, it may be desirable to install additional coils in these sections. It will then usually be possible to set the coils on a reactance tap such that the coils will remain approximately in tune even though the system is split apart, regardless of relative size of the sections. This also avoids the possibility of considerable over-compensation from a coil in case it becomes separated from a large part of the system.

As previously mentioned, the voltage distortion in a transmission system, magnitude of total charging current, and total capacity required in Petersen coils will be somewhat reduced by the installation of additional coils and best results will be secured if they are located near the capacitance centers of the system.

System Neutral Connection

The transformer bank to which the Petersen coil is connected may be either a transformer which is used for the transmission of power or it may be a special transformer for the Petersen coil. The types of transformer connections which can be used are the same as those for system grounding; namely, wye-delta, zigzag auto, wye-wye-delta (for use also as power transformers in parallel with delta-delta connected banks), or transformers connected with one winding zigzag and the other winding delta (for operation in parallel with delta-delta transformers).

One type, known as a "Bauch" or "Bauch-Quenching" transformer, combines the grounding transformer and the adjustable reactor. The grounding transformer is a wye-delta unit. The wye winding is connected to the line and has its neutral solidly grounded. The reactor is connected across an opened corner of the delta winding and is tapped so as to be adjustable for proper tuning.

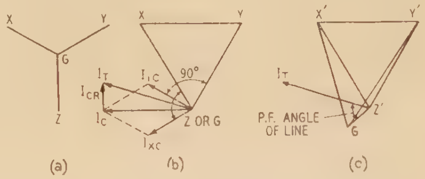


Figure 2. Effect of ground fault and charging current on system voltages, showing: (a) unfaulted line; (b) faulted line, phase Z, at point of fault; and (c) faulted line at point distant from fault

XG, *YG*, *ZG* = Line-to-ground voltages

XY, *YZ*, *ZX* = Line-to-line voltages

I_{YC}, I_{XC} = Charging current to ground (quadrature component) of unfaulted phases

I_{CR} = In-phase component of current to ground of unfaulted phases

I_T = Total current to ground of unfaulted phases

A number of factors enter into the kilovolt-ampere rating of the transformer used with a Petersen coil. If the transformer is a special one used for the coil only, it may be of the same kilovolt-ampere and time rating as the coil. The time rating should generally be at least ten minutes and possibly even continuous, depending upon the method used for isolating permanently grounded line sections. If the coil is to be short-circuited for relaying when a permanent fault occurs, the transformer should have adequate capacity to meet the grounding requirements of the transmission system. This will require at least four or five times the amperes capacity required for Petersen coil operation but the time rating will be on a much shorter basis, usually not over sixty seconds. The higher capacity but shorter time may therefore result in a transformer having a physical size not greatly different than the lower-capacity longer-time transformer required for Petersen-coil operation only without short-circuiting.

Accessory Equipment

Some means of protecting the coil from overload is necessary in case a line conductor becomes permanently grounded. The circuit to the coil can be opened, or the coil can be short-circuited to give ground relaying. Either circuit breakers or motor-operated air-break switches can be used for these purposes, and must be capable of withstanding at least line-to-neutral voltage between contacts and between contacts and ground.

If the Petersen coil is placed in the neutral of a transformer bank used for grounding purposes only, switching equipment in series with the coil can be omitted, but some means should be provided for disconnecting the transformer from the line or bus. At the lower voltages, fuses may be satisfactory, although there is an inherent difficulty in distinguishing between line faults (for which the fuses should not operate), and transformer failures (for which the fuses should operate). Use of a circuit breaker is highly desirable, but it is possible simply to use air-break switches to disconnect the transformer manually when necessary, and to treat transformer faults the same as bus faults.

The Petersen coil ordinarily must be removed from service by one of the above means when tap changing is necessary. An alarm relay and graphic ammeter connected to a current transformer in the permanently grounded lead from the coil are desirable, in addition to relays for operating the switches to short circuit or open the Petersen coil for permanent faults. The current transformer can have a comparatively low voltage rating.

Preliminary Determination of Coil Impedance and Current Rating

The fundamental factors which must be considered to determine the approximate impedance and current rating of Petersen coils are given in the following outline. The detailed methods of calculation are shown in the example of part II.

If the transmission system is not extensive the coil or coils will have a large impedance in comparison with the series impedance of the transmission lines. In this case neither the Petersen-coil current nor the charging current will vary much with faults at different locations and the effect of line impedance can be neglected. With an extensive transmission system, the Petersen-coil impedance will become smaller and the series line impedance larger. The latter then becomes an important factor.

The first step in calculating the coil ratings is to determine the value of zero-sequence capacitive reactance to ground for a short section of transmission line. The next step will depend upon the size of the transmission system to which the coils are to be applied.

Coil Rating—
Short Transmission Systems

For the most simple case, with one coil and a short transmission system, all the capacitive reactance can be considered as lumped at the Petersen-coil location and the series reactance of the line need not be considered. Neglecting positive- and negative-sequence values for the preliminary calculations the inductive reactance of the coil *with* its associated transformer must equal the capacitive reactance of the transmission system to ground.

From this value determined for the reactance of the Petersen coil with its associated transformer, the reactance of the transformer must be subtracted, and the difference divided by three to determine the actual reactance of the Petersen coil itself. This division by three is necessary since per-phase values are ordinarily used and the Petersen coil must carry the zero-phase-sequence current from all three conductors. The current rating is approximately equal to the total residual charging current to ground (determined as previously described) and the voltage rating is equal to the actual Petersen coil ohms multiplied by this current. This voltage is slightly less than the normal line-to-neutral voltage of the system.

In the zero-phase-sequence network, the three phases of the transformer and line are connected in parallel and line-to-neutral voltage applied between them and ground. The per-phase values are, therefore, different than the total values by the factor of three. It would be possible in calculations of an approximate nature to use the total zero-sequence values, which with phase-to-neutral voltage would give the actual coil reactance directly without the necessity of dividing by three. The use of per-phase reactances on the other hand in conjunction with line-to-neutral volts gives the zero-sequence component of the fault current and this must be multiplied by three to get the total fault current. It is much better to use the per-phase values, as the refinement of considering positive- and negative-sequence reactances can easily be added since they are always per phase.

Coil Rating—
Extensive Transmission Systems

If line series reactance must be taken into account, the most simple case is a single transmission line with a Petersen coil at one end. If the line is not over about 100 miles in length, the capacitance can be considered lumped at the ends or in the middle (π or T line). If π lines are used, half the capacitance is lumped at each end and expressed as a capacitive reactance. The capacitive reactance at the far end is then combined with the line series reactance (only zero-phase-sequence values being used for the approximate solution) by subtracting one from the other to obtain an equivalent reactance at the Petersen-coil location.

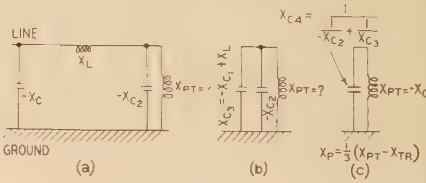


Figure 3. Method of combining line series and shunt capacitive reactances to determine Petersen-coil reactance. The network is reduced to that indicated at (c) and the actual Petersen-coil reactance is then determined by the equation shown

X_{C1} and X_{C2} are the zero-sequence capacitive reactances to ground for the two ends of the line, which are combined as indicated to determine X_{C3} and X_{C4}. See figure 1 for explanation of other symbols

(See transformation a to b of figure 3.) This value must then be combined with the capacitive reactance of the line assumed at the Petersen-coil end (reactances in parallel) to give the equivalent total capacitive reactance at the coil location. (See transformation b to c, figure 3.) The rating of the coil is then obtained in the same manner as in the most simple case where no line series reactance was considered, and is shown in the equation below part c of the figure.

In case of a more extensive transmission system, the line series reactances and lumped shunt capacitive reactances to ground of several short line sections (not over about 100 miles in length) are combined step by step in the same manner to obtain an equivalent total capacitive reactance for the system, referred to the Petersen-coil location or locations.

Positive- and negative-sequence values can be included in the usual manner, although if there are transformers and generators supplying power at different points of the system, the positive- and negative-sequence values usually will be sufficiently low in comparison with the zero-sequence values that they need not be considered in preliminary calculations.

Other Factors in Rating

To provide for proper tuning when a section of the transmission system has been switched off, additional reactance is required in the coil and may be of a lower current rating. This additional reactance must be sufficient to give tuning for the minimum transmission system expected, or down to an arc current value sufficiently low that the arc will be self-extinguishing even though the charging current is not entirely balanced out by the coil current.

The questions of tap steps, tap changers and operating mechanisms, coil insulation and protection against surge voltages, and other design factors have been covered in a recent Institute paper by Mr. E. M. Hunter.[1]

Part II—System Analysis and Computations—By F. Von Voigtlander

Introduction

IN PART I of this paper entitled "Operating Features and Basic Calculations," by W. C. Champe, a discussion of the application of Petersen coils to power systems for the purpose of improving service through the prevention of outages and interruptions due to ground faults is presented. It is the purpose of part II of this paper to present in some detail the method of computation and analysis for the prediction of the behavior of a power system under the condition of single line-to-ground fault with the neutral of the system grounded through a resonant neutral grounding reactor or Petersen coil.

For purposes of discussion, a representative type of power system to which a Petersen coil could be successfully applied is set up and the solution of the required range of reactance and rating of the coil together with resultant ground-fault currents in various branches of the system is presented for two different conditions of system operation. On the basis of the most severe single line-to-ground fault conditions, with the coil applied to the system, the voltages appearing between the phase conductors and ground at the fault and at a station remote from the fault are calculated. To demonstrate the effectiveness of the Petersen coil, results of computations are also given for the fault currents and voltages which the system would experience with the neutral totally isolated. The relative accuracy of the computations and permissible approximations are discussed and an outline of field tests to corroborate design computations and to later check the performance of the Petersen coil after installation is presented.

In the consideration of the application of Petersen coils to a power system, it is assumed here that operating records on the system under consideration have shown that a sufficiently large number of service interruptions due to transitory ground faults have been experienced to warrant the expense of the application of Petersen coils to reduce troubles from this cause. If, for example, 75 per cent of all outages were due to transitory ground faults, a Petersen-coil installation which was, say, only 50 per cent effective, would still provide considerable relief. However, if only 25 per cent of all outages were due to transitory ground faults, the coil installation would have to be much more effective to be justified.

It is of importance, therefore, to carefully analyze the performance of the power system to determine in advance the range of ground fault currents, the relative importance of the in-phase components, and the range of dynamic voltages to ground that may reasonably be expected in operation. These data will serve not only as a basis for the design of the coils, but also to evaluate the probable effectiveness of their installation.

Analysis of a Simple Radial System of Moderate Capacity and Voltage

A general type of isolated-neutral power system has been taken for consideration, consisting of a simple radial network of moderate capacity and voltage, with lines of ordinary wood-pole construction without ground wires and with the conductors sufficiently transposed to keep the normal residual voltage within reasonable limits. This system has been selected as an example of a type to which a Petersen coil can be applied with reasonable assurance of satisfactory results with the possible exception of complete reduction of system overvoltages.

This system shown in figure 1 consists of 33-kv single-circuit, three-phase, 60-cycle lines using wood-pole construction of uniform configuration with number 1/0 copper conductors throughout. The system is supplied by three 1,500-kva generators through a 4,500-kva step-up transformer bank supplying a number of delta-connected transformers along 210 miles of line. All transformers are assumed to be of the two-winding type, delta-delta connected, except at the generating station, which is delta on the generator side but wye on the 33-kv side.

Since the conductors are of reasonable size and the voltage is moderate, corona is no factor and can be eliminated from consideration. Resistance of the conductors could well enough be neglected except that the in-phase component of fault current and line-to-ground voltages are to be computed. It would be expected, however, that the in-phase components of ground-fault current would be too small to sustain the ground-fault arc. The Petersen coil, therefore, would be quite effective in arc extinction if located at any point on this system, but to obtain the maximum effectiveness, particularly in the reduction of system line-to-ground overvoltages for ground faults at all locations, the coil should be located at the capacitance center of the system, which in this case would be at station B. However, practical considerations would probably dictate the location of the coil at the generating station A, where a neutral connection of adequate capacity is already available, though in this location the coil would have but limited effect in the reduction of system overvoltages for ground faults at or near the generating station.

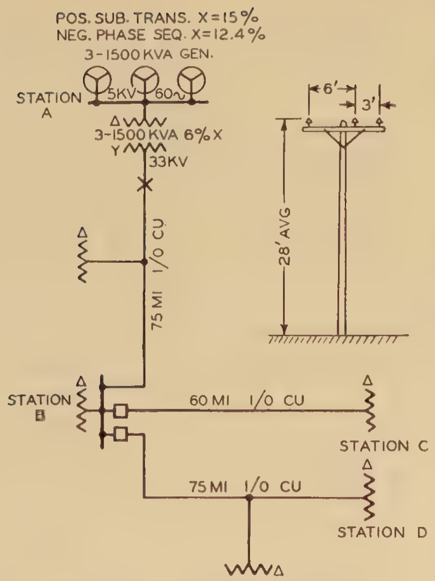


Figure 1. System diagram

Using symmetrical components, the system is divided into its component positive-, negative-, and zero-phase-sequence networks. The impedances of the generators and the transformer bank are known from manufacturer's data which are reduced to ohms on the common voltage base in the normal manner. The electrical characteristics of the transmission lines can be conveniently determined by reference to the tables and curves of Engineering Report No. 37 of the Joint Subcommittee.[3] If test data are not available, earth resistivity may be approximated from the data given in an AIEE paper by R. H. Card.[4] Whenever possible, test data in the vicinity of the system being studied should be used, as earth resistivity may vary quite widely over comparatively small geographical areas and so result in considerable variation in the zero-phase-sequence impedance of the lines. It will be taken here as 50 meter-ohms, a reasonable value for example, in the Great Lakes region. Using the formulas given in tables 2 and 5 and the curves of figures 14, 15, and 16 of Report No. 37, the positive-, negative-, and zero-phase-sequence impedances and admittances of the lines are found as shown in the appendix hereto.

PETERSEN-COIL COMPUTATIONS

Having set up the component networks, a fault location for worst conditions should be chosen. In this case, the worst location for a ground fault would be at the generating station *A*, as this would give the greatest residual current in the system, would require the maximum current and minimum impedance in the Petersen coil at *A*, and would result in maximum voltages to ground on the system, these voltages appearing at station *D*. It is of interest to note that the behavior of this system under these conditions is essentially that of an isolated-neutral system with the exception that only the in-phase components of current appear in the fault and in the positive- and negative-phase-sequence networks.

The required reactance of the Petersen coil can be found directly from the zero-sequence impedance of the system since under fault conditions, the coil is in parallel with this impedance and it is desired to make the reactance of the coil equal in magnitude to the quadrature component of the system zero-sequence impedance, but of opposite sign. When the value of the coil reactance is established, the resultant currents in the fault and in the coil and the component networks can readily be found. The results of these computations carried out in the appendix hereto are summarized in table I. To demonstrate the effectiveness of the Petersen coil the values obtained for the neutral totally isolated are also shown.

The required range of the Petersen coil is now established as 559 to 812 ohms with a capacity of 34 to 23 amperes, respectively. To provide for system growth, changes in operating conditions, and a reasonable factor of safety, this range of values would be extended somewhat both above and below these limits, as necessitated by local requirements. Since the coil would be required to furnish its rated current only for the duration of the fault, the basis for its time rating would depend largely on local methods for clearing permanent ground faults. Time ratings of either ten minutes, 30 minutes, or continuous are usually specified.

It is of interest to consider whether retuning the Petersen coil is likely to be essential if the branch *B-C*, which constitutes 28 per cent of the entire system line mileage, is switched off when the coil is tuned for the complete system. With the coil tuned for the complete system, the neutral impedance is $+j1{,}691$ ohms. With the section *B-C* switched off, the system zero sequence impedance becomes $43-j2{,}450$ ohms. The coil tuned for the complete system would then overcompensate the remaining lines, and a lagging current of $0.39-j10.3$ amperes would appear in the fault. However, even though the coil were not retuned, it would still effect a 57 per cent reduction in fault current and would probably result in fairly effective arc extinguishing for the majority of faults though, of course, satisfactory performance without retuning could be confirmed only by experience.

SYSTEM VOLTAGES TO GROUND

For this assumed system the Petersen coil located at the generating station would be very effective in the reduction of ground fault currents to such low values that the arcs would be self-extinguishing. It is therefore of interest to note the dynamic voltages to ground which may be expected to appear on the conductors for single line-to-ground faults on the system. Precise computation of these voltages is beyond the scope of this paper, but reasonably accurate results for most practical cases can be obtained by applying symmetrical components in the usual manner, neglecting the effects of the load and balanced currents, but including circuit resistances.

Solving for the sequence currents and their distribution in the complete system including the Petersen coil, assuming the fault to ground on phase *Z* at station *A* as before, the voltage drops in the sequence networks can be computed to the point where the system voltages are desired. The resistive components have been included to demonstrate the difference in voltages to ground of the nonfaulted phases at points remote from the fault, caused by the introduction of the quadrature component of zero-sequence voltage.

The results of these voltage computations as carried out in the appendix hereto are given in table II. The values for

Table I. System Impedances and Fault Currents

	Complete System		Section B-C Switched Off	
	Petersen Coil	Neutral Isolated	Petersen Coil	Neutral Isolated
Positive-phase-sequence impedance (ohms)	$+j50.8$	$+j50.8$	$+j50.8$	$+j50.8$
Negative-phase-sequence impedance (ohms)	$+j44.5$	$+j44.5$	$+j44.5$	$+j44.5$
Zero-phase-sequence impedance (ohms)	57,900	$49-j1{,}690$	139,700	$43-j2{,}450$
Total equivalent impedance (ohms)	57,900	$49-j1{,}595$	139,700	$43-j2{,}355$
Ground fault current (amperes)	0.99	$1.11+j35.8$	0.41	$0.44+j24.3$
Petersen-coil current (amperes)	$-j33.8$		$-j23.4$	
Petersen-coil impedance (ohms)	$+j559$		$+j812$	

the neutral totally isolated are also shown for comparison.

Figure 2 shows the vector relations of the system voltages at station *A* (the location of the fault) and at station *D* (remote from the fault). The ground fault is on phase *Z* so that its potential at the fault is reduced to ground potential or zero. The voltages of phases *X* and *Y* to ground then become equal to the line-to-line voltages. At station *D*, 150 miles away, the line-to-line voltage triangle $X'Y'Z'$ is equal to and in phase with the line-to-line voltage triangle XYZ (load and balanced components having been neglected), but $X'Y'Z'$ in this case has been displaced upwardly and to the right. At station *A*, the line-to-line-and line-to-ground-voltage triangles coincide. At station *D* the line-to-line-voltage triangle $X'Y'Z'$ is displaced from the line-to-ground voltage triangle $X'Y'G$ due to the rise and line-angle shift of zero-sequence voltage progressing along the line from the fault, so that the magnitudes of the voltages to ground at *D* no longer equal those at *A*.

These voltages given in table II are the dynamic voltages to ground sustained by the system for the duration of the fault. Coincident with the fault, tests have shown that voltage transients of the order of 100 kv crest may also be experienced. These voltages, both dynamic and transient, are *not* the result of the operation of the properly engineered modern Petersen coil, but are an attribute of operation with a flexible neutral.

The effect of the Petersen coil in reducing the dynamic voltages which may be experienced during ground faults deserves note, as by means of the coil these voltages may be limited to values safely within the ratings of equipment connected from line-to-ground, which otherwise might be damaged.

The voltages as computed for this system represent the maximum range of dynamic voltages that might be expected because the fault has been placed at the Petersen coil which is at one end of the system so that in this case it has had but limited effect in the reduction of system overvoltages. If a fault location had been chosen elsewhere on the 33-kv system, a greater reduction in these overvoltages would have been effected. The maximum reduction would be experienced for faults at station *D*, as the lagging reactive current from the Petersen coil would then flow out onto the system to balance the leading capacitance current from the lines and thereby reduce the capacitance current flowing through the system series impedance. If Petersen coils were located, for example, at both stations *A* and *D*, dynamic overvoltages to ground on this system would be eliminated, that is, they would be reduced to line-to-line voltages when one phase was grounded.

Accuracy of Computations

In making calculations of power-system fault currents and voltages, the question naturally arises as to what accuracy can reasonably be expected of the results. With the modern methods of computation and with convenient and accurate means available for calculating system impedance characteristics, it will generally be found that the greatest unknowns in the computations are the effects of the various empirical factors upon the system admittance to ground, earth resistivity, and the effects of harmonics.

Tests on a number of systems over quite a range of voltages and configurations have shown the measured values of admittances of short sections of line to be consistently greater than the calculated values. In the author's experience, these differences on well-maintained systems where complete data is available and where corona is no factor, have been found to uniformly approximate ten per cent. Where test data are not available, the calculated values of unit admittance may be increased by this amount with resultant improvement in accuracy. On high-voltage systems where corona is a factor, the calculation of the system admittance is complicated by the necessity for evaluating the capacitance-shunting resistance equivalent of the corona loss, which itself is subject to considerable variation, and by the direct effect of corona on the system capacitance. In making computations in which corona must be considered, it is well to bear in mind also that the corona loss of a system with one conductor grounded is considerably greater than the balanced corona, as has been discussed in various articles on this subject.

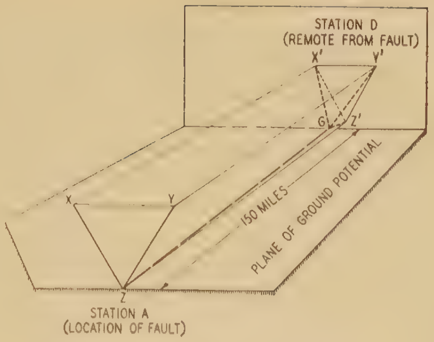


Figure 2. Voltage diagram

Table II. Voltages to Ground for Complete System

		Phase X	Phase Y	Phase Z
At station *A* (fault location)	Petersen coil	33,000	33,000	0
	Neutral isolated	34,500	34,500	0
At station *D* (remote from fault)	Petersen coil	35,000	35,800	2,780
	Neutral isolated	36,500	37,500	2,880

If test data are available on the earth resistivity in the territory of the system, the errors due to this factor can be largely eliminated. Where no test data are available, but reasonably accurate estimates can be made, resulting errors in computing zero-sequence impedance may be of the order of ten per cent to 30 per cent. In extreme cases of unsuspected high earth resistivity though, these errors may be greater. However, large errors in zero-sequence impedance will generally not result in proportional errors in fault-current computation because the impedance is usually a smaller factor than the admittance.

All computations involving residual current are subject to errors due to the effects of harmonics in that current. Errors in results due to these harmonics do not usually in practice become as serious as might be expected. However, the possibility of the system being resonant to certain harmonics should not be overlooked, as this can be predicted fairly well from the impedance characteristics of the system.

Tests have shown that when all pertinent factors have been taken into account and reasonably accurate basic data are available, the ground fault currents and voltages can be calculated to within less than ten per cent of their measured values. The in-phase component of system fault currents, however, is subject to considerably greater error, because it is usually a small portion of the total current and is displaced from it by approximately 90 degrees, and because of the difficulty of accurately evaluating leakage and corona.

Permissible Approximations

In any more or less extended analysis of this sort it is, of course, desirable to make such approximations and simplifications as may be made without introducing errors inconsistent with the expected accuracy of the computation. For instance, in the example under consideration, hyperbolic correction factors could have been applied to the distributed constants of the system with the resultant difference of about 1 per cent in the value of system characteristics from that computed by the more approximate methods of lumping the characteristics into the three sections. It is therefore seen that while the additional labor of employing hyperbolic functions in such a simple system would be entirely unwarranted, in an extensive system, it might easily be justified, particularly if the effects of loads and balanced currents were to be considered.

As shown in table I, the magnitude of fault current is but very slightly affected by the resistances in this system and obviously for calculations in which it was not necessary to determine the in-phase component, the resistances could easily be neglected. However for example, if the conductors had a high resistance-to-reactance ratio, or if considerable corona was present, the resistance might easily have become an important factor.

There is always the danger of one attempting to apply the results of approximation in simple cases to complex cases where such approximations may lead to great error. It is, therefore, always advisable to carefully consider the system involved and to observe the relative magnitudes of the various factors which it is proposed to neglect. Approximations, particularly of the rule-of-thumb type, frequently serve to magnify the errors, especially on large and extensive systems, to a point where the computations may be of little value. Considerable experience has shown it advisable to set up the component phase sequence networks completely so that the relative magnitudes of the various factors become apparent before attempting to resort to approximations.

In spite of the various doubtful factors which may come into computations of this sort, the results obtained when based on reasonably accurate system data and on well-considered choice of intangible factors, will amply bear out and justify the efforts put into the work. Although a plus or minus ten per cent error may seem large compared to the accuracy of many other electrical computations, this error becomes small when compared to the error that results from attempting to design a Petersen-coil system without making these detailed calculations.

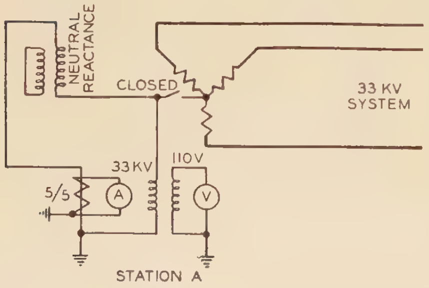


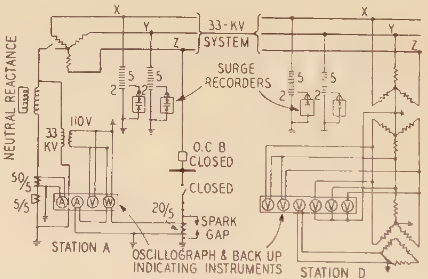
Figure 3. Diagram of connections for tuning neutral reactance

Field Tests to Corroborate Design Computation

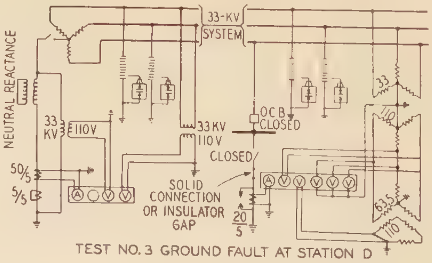
Since the installation of a Petersen coil generally involves an appreciable investment, if there is much doubt about the accuracy of the power-system data earth resistivity, etc., field tests to check the results of calculations are easily justified. Before making any tests, however, complete computations should be made in advance, based on the best data obtainable, so that some approximation of the range of expected results can be obtained. By the use of a transformer of the required reactance and rating, a Petersen coil can be simulated if a neutral connection can be made available so that the tests can be made under conditions closely approximating expected operating conditions.

Figure 3 shows a schematic diagram of test connections for tuning a system to resonance with the neutral reactance. Tuning can be accomplished either by varying the reactance in the neutral or by varying the system admittance by switching lines on or off the system as required.

Figure 4 shows schematic diagrams for making the necessary simultaneous surge-recorder, oscillograph and indicating-instrument measurements of neutral voltage displacement, neutral current, fault current, phase angle between fault current and residual voltage, phase-to-phase voltages, phase-to-ground voltages, residual voltages, and transients during the time of the application of solid ground faults and ground fault arcs at the proposed Petersen-coil location (station *A*) and at the remote point of the system (station *D*).



TEST NO. 2 GROUND FAULT AT STATION A



TEST NO. 3 GROUND FAULT AT STATION D

Figure 4. Diagram of system ground-fault test connections

From the results of such tests as outlined, sufficient data can be made available to accurately establish the system's electrical ground-fault characteristics so that the computations can be checked. During the ground-fault tests, simultaneous observations may be made on neighboring communication circuits and factors such as mutual coupling and earth resistivity may be determined.

Field Tests to Check Petersen-Coil Performance

Field tests to check performance of the installation after the Petersen coil has been designed, manufactured, and installed on the system are essential to check the performance of the coil and the system under the various operating conditions likely to be encountered. The setup for these tests would be quite similar to the setup for tests to determine the system's electrical characteristics as outlined in figures 3 and 4. The tests would be carried on in quite a similar manner with the possible addition of tests at various other locations and under perhaps a wider range of operating conditions. If any form of automatic clearing of permanent ground faults has been installed, the functioning of such equipment should also be observed and checked by test.

Tests with the coil tuned for the entire system but with parts of the system switched off should also be made to determine the necessity for precise tuning and to determine the stability of arcs of various current values on the system. In addition, tests can be made of bushing-type current-transformer ratios, effectiveness of relays, effectiveness of lightning arresters, rod gaps, protector tubes, etc., so that a large amount of very useful data can be obtained on the characteristics of the system during abnormal operating conditions.

With the system in reasonably good operating condition all the tests as outlined should be carried on without adversely affecting service on the system during the time of the tests. Since only single-phase ground faults are involved, barring equipment failures such as lightning-arrester failures, bushing flashovers, and similar failures, which are commonly experienced on isolated-neutral systems during conditions of single line-to-ground faults, no appreciable effect on the phase-to-phase voltages will ordinarily be noticed.

Conclusions

1. Petersen coils have a definite field of application in improving the performance reliability of a transmission system. However, there are many factors which need to be considered in determining their probable effectiveness in a given installation, including:

(*a*). The relative number of transitory single line-to-ground faults vs. faults from all causes.

(*b*). Magnitude of the in-phase component of fault current.

(*c*). Overvoltages to ground that may occur with faults at different locations.

2. The electrical circuit characteristics of the system during line-to-ground faults must be determined to properly ascertain the coil characteristics. These can be calculated reasonably accurately and substantiated by test.

3. The layout of the system has an important effect on the voltage and current conditions during ground faults. This is especially true if a long section of small conductor line connects two large capacitance centers of the system.

4. Dynamic overvoltages to ground considerably in excess of line-to-line voltages may be experienced during single line-to-ground faults even though the system is equipped with a properly tuned Petersen coil.

5. The ground-fault characteristics of a system both before and after the installation of Petersen coils may be confirmed by relatively simple tests which need not interfere with normal operating conditions. These tests should include measurements of earth resistivity, overvoltages, effectiveness of protective equipment, effect on paralleling communication systems, etc.

Appendix

System Impedances

The positive- and negative-phase-sequence networks of the assumed system are shown in figures 5 and 6 for the fault at station *A*. The portions not shown carry no current. The zero-phase-sequence-line impedances may be determined from table 2 and curves of figures 15 and 16 of Engineering Report No. 37 of the Joint Subcommittee:[3]

$Z_{11} = 0.697 + j1.46$ for 1/0 copper conductors with mean spacing of 5.45 feet and earth resistivity of 50 meter-ohms

$Z_{12} = 0.09 + j0.71$

$Z_0 = Z_{11} + 2Z_{12}$

$= 0.877 + j2.88$ ohms per mile, zero-sequence impedance

The zero-sequence line admittance may be determined from table 5 and figure 14 of Engineering Report No. 37 of the Joint Subcommittee.[3] With line conductors as above at 28 feet average height:

$$C_0 = \frac{0.179}{2\log\frac{4h}{d} + 2\left(2\log\sqrt{\frac{4h^2}{S_{12}^2}+1}\right)}$$

$= 0.00683$ microfarad per mile, zero-sequence capacitance

$= -j388{,}000$ ohms per mile, shunt impedance or $+j2.57 \times 10^{-6}$ mhos per mile, shunt admittance

Zero-sequence network is as shown in figure 7 and reduces to $Z_0 = 49 - j1{,}690$ ohms.

Petersen-Coil Computations

COMPLETE SYSTEM

Admittance corresponding to above zero-sequence impedance is $Y_0 = (17.3 + j591) \times 10^{-6}$ mho.

Neutral admittance should then $= Y_{PT} = -j591 \times 10^{-6}$ mho or $X_{PT} = +j1{,}691.5$ ohms.

Petersen-coil reactance $(X_P) = {}^1/_3(X_{PT} - X_{TR}) = {}^1/_3(+j1{,}691.5 - j14.5) = +j559$ ohms.

The zero-sequence impedance of the system including the Petersen coil then reduces to 57,900 ohms and the fault current becomes

$$I_f = \frac{33{,}000\sqrt{3}}{57{,}900 + j50.8 + j44.5}$$

Neglecting the *j* terms as insignificant,

$I_f = 0.99$ ampere

The current in the coil then is found to be $-j33.8$ amperes and the current in the zero-sequence network becomes $0.33 + j11.27$ amperes.

SECTION B-C SWITCHED OFF

With section *B-C* switched off the zero-sequence network becomes as shown in figure 8 which reduces to

$Z_0 = 43 - j2{,}450$ ohms

or

$Y_0 = (7.16 + j408)\,10^{-6}$ mho

Neutral admittance should then $= Y_{PT} = -j408 \times 10^{-6}$ mhos or $X_{PT} = +j2{,}450$ ohms. Petersen-coil reactance $(X_P) = {}^1/_3(+j2{,}450 - j14.5) = +j812$ ohms.

The zero-sequence impedance of the system including the Petersen coil then reduces to 139,700 ohms and the fault current becomes 0.41 amperes, with a coil current of $-j23.4$ amperes.

With the coil tuned for the complete system but with section *B-C* switched off the zero-sequence impedance becomes $Z_0 = 213.5 + j5{,}460$ ohms, and

$$I_f = \frac{33{,}000\sqrt{3}}{213.5 + j5{,}460 + j50.8 + j44.5}$$

$= 0.39 - j10.3$ amperes

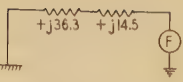


Figure 5. Positive-phase-sequence network

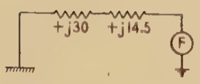


Figure 6. Negative-phase-sequence network

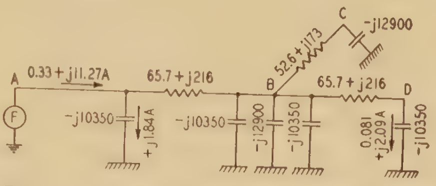


Figure 7. Zero-phase-sequence network for complete system

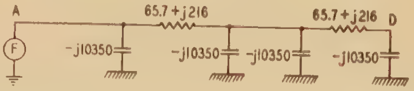


Figure 8. Zero-phase-sequence network with line section B-C switched off

Computation of Voltages

From the coil computations the current in the zero-sequence network is found to be $0.33 + j11.27$ amperes. Current distribution in the network gives $+j1.84$ amperes through the admittance at *A* and $0.081 + j2.09$ amperes through the admittance at *D*.

VOLTAGES AT THE FAULT (STATION *A*)

Positive sequence:

$$E_1 = \frac{33{,}000}{\sqrt{3}} - (0.33 \times j50.8)$$
$$= 19{,}050 - j17 \text{ volts}$$

Negative sequence:

$$E_2 = 0 - (0.33 \times j44.5) = 0 - j15 \text{ volts}$$

Zero sequence:

$$E_0 = 0 - (+j1.84 \times -j10{,}350)$$
$$= -19{,}050 \text{ volts}$$

From symmetrical components and neglecting the above *j* voltage terms as insignificant:

$$E_x = a^2E_1 + aE_2 + E_0$$
$$E_y = aE_1 + a^2E_2 + E_0$$
$$E_Z = E_1 + E_2 + E_0$$

where $a = -0.5 + j0.866$ and $a^2 = -0.5 - j0.866$

Phase X to Ground	Phase Y to Ground	Phase Z to Ground
−9,525 − *j*16,500	−9,525 + *j*16,500	19,050
0	0	0
−19,050	−19,050	−19,050
−28,575 − *j*16,500 33,000 volts	−28,575 + *j*16,500 33,000 volts	0 0 volt

VOLTAGES AT STATION *D* FOR FAULT AT *A*

Positive- and negative-sequence voltages at *D* will be the same as at the fault (see above) as these two networks are considered as carrying no current between A and D in this case.

$$\text{Zero-sequence voltage} = 0 - [(0.081 + j2.09) \times -j10{,}350] = -21{,}700 + j840 \text{ volts}$$

$$\text{Phase } X \text{ to ground} \left\{ \begin{array}{c} -9{,}525 - j16{,}500 \\ 0 \\ -21{,}700 + j840 \\ \hline -31{,}225 - j15{,}660 \\ 35{,}000 \text{ volts} \end{array} \right.$$

$$\text{Phase } Y \text{ to ground} \left\{ \begin{array}{c} -9{,}525 + j16{,}500 \\ 0 \\ -21{,}700 + j840 \\ \hline -31{,}225 + j17{,}340 \\ 35{,}800 \text{ volts} \end{array} \right.$$

$$\text{Phase } Z \text{ to ground} \left\{ \begin{array}{c} 19{,}050 \\ 0 \\ -21{,}700 + j840 \\ \hline -2{,}650 + j840 \\ 2{,}780 \text{ volts} \end{array} \right.$$

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Discussion

H. M. Rankin and **R. E. Neidig,** nonmember (Metropolitan Edison Company, Reading, Pa.): *Part I—Operating Features and Basic Calculations*—by W. C. Champe. The author has covered the ground in a brief but clear and instructive manner. There are, however, a few points on which we wish to comment, as follows:

Lightning Arrester Rating. The author says that with multiple coil installations it may be possible to reduce the rating of lightning arrester below line-to-line voltage. We believe such practice would be questionable, as sectionalizing the system might readily leave any one section isolated with one coil, and the high impedance of the coil would maintain line-to-line voltage to ground on two conductors if the third were grounded.

Advantages of Petersen Coil. Records which we have taken with an automatic oscillograph have never indicated higher voltage to ground than 1.7 times normal line-to-neutral voltage. Our equipment is designed for voltage to ground equal to normal line-to-line voltage.

Transpositions. On existing systems, particularly some of the older ones, it may be difficult and expensive to obtain the proper number of transpositions. We have found it possible in some cases to balance one section of line against another section having a different arrangement of conductors. This, of course, can only be done providing it is possible, when one of these lines is out of service, to cut the residual current to a satisfactory value by detuning the coil still keeping within limits of satisfactory coil operation.

Number of Coils Required. It would seem that the number of coils would depend principally on the possible sectionalized operation of the system rather than on relaying requirements. We are considering the installation of two coils on a system having at present grounding transformers at four locations. The two coils would be installed in the neutrals of two of the grounding transformers and equipped with short-circuiting switches. At the other two locations, we are proposing to simply install neutral grounding switches with suitable automatic control equipment to operate similarly to the short-circuiting switches used with the Petersen coils.

Accessory Equipment. The author states that if the Petersen coil is placed in the neutral of a transformer bank used for grounding purposes only, switching equipment in series with the coil can be omitted. We believe this is somewhat questionable as it might be desirable to use the grounding transformer as such during maintenance work on the coil, in which event means of disconnecting the coil and grounding the neutral would be necessary.

In our installations, we have provided an operation counter as well as alarm relay and graphic ammeter. We have found this advantageous as the chart speed of the ammeter is not great enough to separate the lines drawn by successive operations. For instance, in a recent storm we had five operations of a Petersen coil within a period of 12 seconds. In this particular case, an operator happened to be watching the ammeter and saw the five operations of the needle, which indicated different values of current for each operation although there was only one line registered on the chart. The counter recorded all five operations.

Part II—System Analysis and Computations—by F. Von Voigtlander. Our only comments on Mr. Von Voigtlander's very instructive paper are in the nature of operating results, as follows:

The Metropolitan Edison Company has installed three Petersen coils—one at Reading, Pa., one at Middletown, Pa., on its 66-kv system, and one at Holtwood, Pa., on the system of the Pennsylvania Water & Power Company, with whom they are interconnected. These coils operate on a total of 308 miles of circuit and are tuned for 112, 95, and 101 miles, respectively. They were placed in operation in October 1937, and up to June 16, 1938, the record is briefly as follows: Total faults on 66-kv system—72. Transient faults—64, or 89 per cent of total. Transient faults cleared by Petersen coils—50, which is 78.2 per cent of all transient faults, or 69.5 per cent of all faults on the 66-kv system.

Field Tests. Staged tests were made on this system under various conditions, the worst case being with 25 per cent of the lines for which the coils were tuned disconnected but with no retuning of the coils. These tests were made by establishing an arc to ground across a string of suspension insulators by means of a fuse, and were in all cases successfully cleared within times ranging from one-half cycle to seven cycles. In recent storms, lightning flashovers have also been successfully extinguished with as much as 25 per cent of the line mileage for which the coils were tuned disconnected.

A. W. Gothberg (Public Service Electric and Gas Company, Newark, N. J.): In the paper by W. C. Champe and F. Von Voightlander on "System Analysis for Petersen Coil Application," it is stated that in considering the installation of Petersen coils it should be kept firmly in mind that they have no effect on phase-to-phase faults as such.

This limitation is a severe handicap to an effective installation of a Petersen coil on a system having an appreciable amount of wood-pole transmission. Figures have been published indicating that as many as 75 per cent of the faults on a transmission system are phase-to-phase and as many as 85 per cent of all faults are due to lightning. This clearly indicates that lightning is causing a majority of all faults and on wood-pole lines it is admitted that most of them result in phase-to-phase faults.

A paper has been published in the January 1937 issue of Electrical Engineering entitled "Lightning Protection for Transmission Lines," in which a wood-pole-line design was presented which eliminated or reduced the number of phase-to-phase faults due to lightning. Although this design used lightning-protector tubes on one phase of a three-phase line, it can be made particularly applicable to a system using a Petersen coil by simply substituting a suitable gap for the lightning-protector tubes.

In brief, it would consist of making one phase of each circuit a shielding conductor by locating it so that the remaining phases will be shielded from direct lightning strokes. Lightning currents could be drained from the shielding conductor by means of suitable gaps connected to ground. This would result in a single-phase fault which could be cleared by a Petersen coil. The remaining phases could be isolated from the shielding conductor and the gap ground circuits by insulation sufficient to prevent phase-to-phase faults. On double-circuit lines, gaps could be installed on the two top shielding conductors. It is important that the same phase of each circuit be on the top arm so that in the event of a stroke involving the two top conductors, a phase-to-phase fault does not result. Methods of determining the amount of insulation required on the pole top and the frequency of the gaps along the line can be found in the paper mentioned above.

Limited experience with this type of construction has shown its ability to eliminate phase-to-phase faults.

This proposed design of wood-pole line should make the effectiveness of a Petersen coil on a wood-pole line approach or equal to the effectiveness of a Petersen coil on a steel tower line equipped with ground wires. It would overcome one of the most serious limitations in the application of a Petersen coil to a system having wood-pole transmission.

W. D. Hardaway (Public Service Company of Colorado, Denver): The authors have presented in convenient and useful form, methods for making basic calculations for the application of Petersen coils to transmission systems. They mention the possibility of unsuccessful coil operation due to corona current when applied to high-voltage systems operating with small conductors or at high altitude. In this connection it would be of interest to have stated the maximum values of corona current which are being successfully interrupted by Petersen-coil operation. On the Colorado 100-kv system, fault currents of from 20 to 25 amperes are quenched without difficulty, and North and Eaton report fault currents of from 38 to 50 amperes on the Michigan 140-kv installation (Elec. Eng., vol. 53, page 67). It appears improbable that these values will be greatly exceeded on other systems.

The authors have called attention to the difficulty in properly relaying an isolated neutral system for single-phase faults to ground. Solidly grounding, with the addition of proper relays, will usually solve this problem. However, the application of a Petersen coil may be materially less expensive than this remedy, and has the further advantage of improving continuity of service. Also it appears that the Petersen coil eliminates the excessive harmonic overvoltages frequently present under arcing ground conditions on isolated-neutral systems.

E. M. Hunter (General Electric Company Schenectady, N. Y.): Continued interest is being shown in the Petersen coil as a service-protective device. At the last winter convention it was reported that there were seventeen coils in the United States, the majority of which have been applied in the last year or so. In the last few months seven more applications have been made, bringing the total to 24. Naturally, some application and operating experience is now available on these protective devices and this experience is the basis of the comments prepared on this paper.

In-Phase Component of Fault Current

In part I of the paper it is stated "The in-phase component must be carefully checked to make sure that it will not be large enough to maintain the arc readily and prevent extinction by the Petersen coil."

I am sure it would be of interest if the authors would give their views on the magnitude of the in-phase component of fault current beyond which it would be undesirable to apply Petersen coils.

Although system analysis and operating experience on existing installations is limited, it indicates that on medium-voltage systems (66 kv and below), the in-phase component of the fault current should not exceed 20 to 25 amperes. This relatively low value of current apparently does not maintain the arc. This is likewise true on high-voltage systems (110 kv and above) unless the system has considerable corona loss. When there is corona and the system is extensive, then the in-phase component of current may be a problem, although in all of the applications made to date, successful arc extinction has been reported with in-phase components of current up to 50 amperes. It appears that the in-phase component of current need only to be considered if there is corona.

System Overvoltages During Ground Faults

In part II of the paper, an analysis is made of the overvoltages on a system (Figure 1, part II) with and without a Petersen coil in the neutral. It shows that with a ground fault on one of the phases at a point in the system adjacent to the station where the Petersen coil is located, the voltage to ground on the two healthy phases increases with distance from the fault point. The magnitude of these voltages is summarized in table II, part II.

Referring to this table, it is seen that the voltages with the Petersen coil increase approximately nine per cent above the system line-to-line voltage at a point 150 miles away from the fault. Since the calculations from which these voltages were derived neglects load current, they undoubtedly represent maximum values. Inductive reactive load current would, in general, have a tendency to reduce these voltages. It should be noted that they do not exceed the maximum permissible line-to-ground voltages recommended for protective equipment on such a system. Also, they are lower than if the neutral were free. These voltages would also be lower if the Petersen coil had been located at station *B* instead of a station *A*. System analysis has shown and operating experience has verified the fact that when overvoltages in remote sections of the system away from the ground fault are likely to be excessive, several coils correctly placed in the system will limit these overvoltages to reasonable values.

It is interesting to note that overvoltages at the point of fault with the system neutral isolated are much higher than if the neutral were grounded through a Petersen coil. For example, on this system of figure 1, part II, the voltages at station *D* for ground faults at station *D* have been calculated for the condition of (1) the system neutral isolated at *A*, (2) the system neutral solidly grounded at *A*, and (3) the system neutral grounded through a Petersen coil at *A*. This study has been made with all three generators in service and also with only one generator in service. The results of this study are summarized in table I.

Table I

Voltage to Ground	Neutral Isolated	Neutral Grounded	Petersen Coil
Three Generators in Service			
Phase *X*	38 kv	24 kv	33 kv
Phase *Y*	41 kv	22 kv	33 kv
Phase *Z*	0	0	0
One Generator in Service			
Phase *X*	41 kv	21 kv	33 kv
Phase *Y*	44 kv	20 kv	33 kv
Phase *Z*	0	0	0

With only one generator in service and the neutral isolated, the voltages are relatively high. This may be explained by the fact that on this system a condition of partial series resonance is obtained. It should be noted that with the Petersen coil in the neutral, the voltages on the two healthy phases do not exceed the system phase-to-phase voltage.

The authors also mentioned high transient overvoltages on the system at the time a ground fault occurs. I would like to have the authors' comment on this further and possibly show how these overvoltages occur and how they may be calculated. Experience indicates that if these overvoltages do occur, they are of a very short time duration, so short in fact that they do not record on a magnetic oscillograph. The magnitude also must well be within the limits of insulation strength of connected apparatus because there is no indication that they do any appreciable damage.

Accuracy of Calculations

The authors state that their system analysis gives results which can be substantiated by tests within a ten per cent error. The experience available to date on Petersen coil applications leads to the conclusion that the methods used by the authors are not necessarily that accurate.

For example, the in-phase component of current for the system analyzed in part II of the paper has been calculated by the authors to be 0.99 ampere. Experience on 11 33-kv applications of Petersen coils leads me to believe that this particular system would have an in-phase component of current between ten and 15 amperes. This would result from leakage on apparatus and also harmonics which appear to have been neglected or omitted from the authors' calculations. This current would vary with the weather, the higher value being noted during stormy periods.

With regard to the charging current in a ground fault which must be compensated by lagging current in the Petersen coil, the experience previously mentioned indicates that this system should have between 42 and 46 amperes instead of the 34 amperes given by the authors for charging current for the 210 miles of line. Possibly this discrepancy may be explained by the fact that in their calculations they have calculated only the zero sequence capacity of the transmission line alone and have made no allowance for the capacitance or apparatus, insulators, bushings, poles, etc. These other effects have a tendency to increase the charging current, making it higher than the current given by the formulas used by the authors.

As suggested by the authors, measurements to substantiate calculations of charging currents are advisable when experience is limited.

W. W. Lewis (General Electric Company, Schenectady, N. Y.): Messrs. Champe and Von Voigtlander give a very useful summary of the conditions that should be considered in the application of Petersen coils. I am especially interested in their discussion of the accuracy of computations on pages 14 and 15 of the preprint and wish to comment briefly on this feature.

If the tests are made carefully and all the conditions are known, and if the calculations are accurately made for the same conditions as existed in the tests, then the results of the tests and calculations should certainly check. However, usually it is not possible to know all of the conditions of either test or calculation sufficiently well to obtain better than an approximate check. A couple of examples will illustrate this point.

When the Public Service Company of Colorado were considering the application of a Petersen coil on their Shoshone-Denver line, we made some calculations, assuming the average spacing of the conductors to ground as the height at the towers minus two-thirds of the sag. This is probably a fair assumption for level stretches, but as much of this line is in the mountains and spans from hill-to-hill over gulches and canyons, the average height obtained from a profile by planimeter would probably be considerably greater than the height assumed. Allowance was made for the increase in capacitance due to corona and account was taken of the capacitance of the line insulators, apparatus, bushings, disconnecting-switch insulators, and transformer windings. The calculated fault current was 92 amperes capacitance current and 95 amperes including in-phase current due to corona, but neglecting harmonics, for the approximately 187 miles of line. The power company then made some tests in which the neutral was isolated and one conductor grounded. Fault current to ground and voltages to ground were measured with oscillograph, ammeter, and voltmeter. Tests were made at three different points on the system, namely, at the Denver and Shoshone ends and at an intermediate point, Leadville. Reduced to the same voltage basis of 95,000 volts, these tests showed, respectively, fault currents of 123, 101, and 137.5 amperes for the approximately 187 miles of line.

Finally, when the Petersen coil was put into operation, the Petersen-coil currents for ground faults at Leadville and Denver were measured at the tuned setting of the coil ("Test and Operation of Petersen Coil on 100-Kv System of Public Service Company of Colorado," by W. D. Hardaway and W. W. Lewis, ELECTRICAL ENGINEERING, June 1938, pages 295–302). The readings were 98 and 96 amperes, respectively. Thus the calculations checked fairly closely the measured Petersen-coil current but did not check at all well the measured ground fault current.

In another case, a single-circuit 115-kv line with two ground wires was tested. The line was opened up at both ends by disconnecting switches. Low-tension single-phase voltage was placed on the open-circuited line between the three conductors in multiple and ground. Voltage, current, and watts were read. From these readings the zero-sequence capacitance of the line was found to be 0.211 microfarad. The capacitance of the conductors was calculated, assuming an average spacing to ground equal to the height of the conductors at the towers minus two-thirds of the sag. This capacitance, added to that of the line insulators and disconnecting-switch insulators, and assuming no corona, gave a total zero-sequence capacitance of 0.172 microfarad. In this case the tested capacitance was 22 per cent higher than the calculated.

Either Mr. Hunter or I have made calculations for all of the Petersen coils that have been installed in this country and have made ground-fault tests after installation in most cases. From these tests we have worked out the empirical relations shown in figures 1 and 2, for single-circuit lines. These relations can be used as a guide in the selection of Petersen coils.

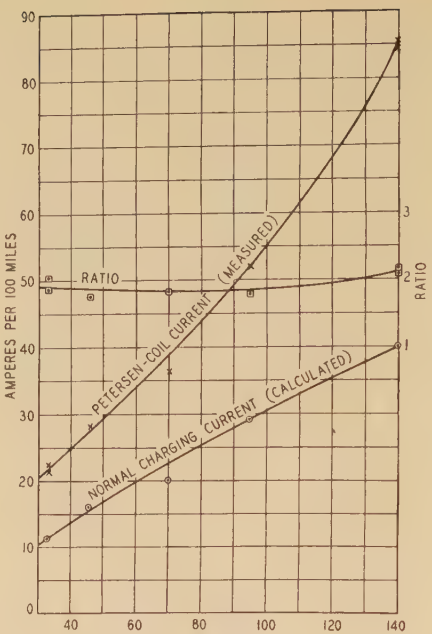


Figure 1

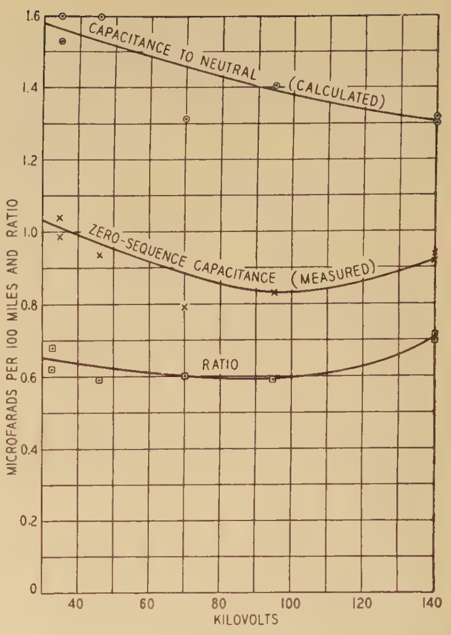
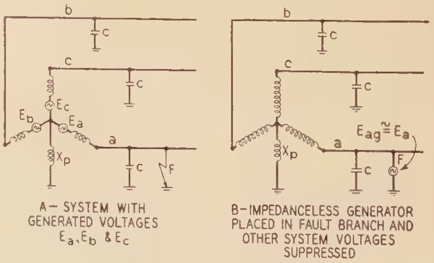


Figure 2

P. A. Jeanne (Bell Telephone Laboratories, Inc., New York, N. Y.): I have been quite interested in the recent activity in the application of Petersen coils in this country, particularly as it has been my privilege, as a member of project committee 2*J* of the joint subcommittee on development and research of the Edison Electric Institute and Bell System, to participate in studies of current-limiting devices, including the tests on the first of the more recent Petersen-coil installations in this country, made in 1931. I think that Mr. Champe and Mr. Von Voigtlander have brought out quite well most of the features requiring consideration in the application of Petersen coils. The comments which I have on the paper are made chiefly from the standpoint of clarifying certain ideas. In the introduction to Mr. Champe's paper (advance copy), the statement is made that with a Petersen-coil system the inductive reactance, most of which will be in the Petersen coil or coils, will be approximately equal to the capacitive reactance of the two unfaulted conductors to ground. I think this statement requires modification because one might assume from it that the proper reactance for the Petersen coil would be one determined from the sum of the direct capacitance to ground of the sound phases, while in fact it is determined from the sum of the direct capacitance to ground of all three phases. I think perhaps the author had in mind the fact that in a Petersen-coil system the charging current of the two sound phases equals the Petersen-coil current, a fact which might readily lead to the statement cited. Perhaps I can make this clear by reference to figure 3. Figure 3(a) represents a balanced three-phase power system grounded through a reactor and with a fault on phase *A*. Now if the only voltage in the system were that in phase *A* we could immediately see that for minimum current in the fault the neutral reactance should just equal in magnitude the capacitive reactance of the two sound phases to ground, as that would provide the parallel resonant condition sought. However the presence of the voltages E_b and E_c in the sound phase branches subjects them to higher voltages to ground than that across the reactor and the requirement for resonance is not immediately apparent. Now by a well-known theorem, the current in a particular branch of a network can be determined if an electromotive force equal to that which would exist across an open circuit in that branch is introduced into the branch and the other voltages in the system suppressed. If we apply this idea to the circuit under consideration, as in figure 3(b), the current in the fault branch will be the same as it would be with the regular voltages impressed as in figure 3(a). It can be seen immediately that, in the circuit of figure 3(b), the direct capacitances-to-ground of all three conductors are in parallel with the reactor, so that to secure the parallel resonant condition desired, the reactance of the Petersen coil must be made equal in magnitude to the capacitive reactance of the sum of the direct capacitance to ground of all *three* conductors. The same thing could of course be shown by



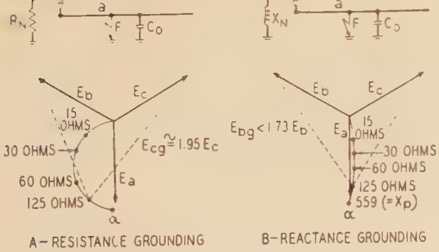
A—SYSTEM WITH GENERATED VOLTAGES E_a, E_b & E_c

B—IMPEDANCELESS GENERATOR PLACED IN FAULT BRANCH AND OTHER SYSTEM VOLTAGES SUPPRESSED

Figure 3. Petersen coil

solving the network of figure 3(a) for a value of reactance which would make the current through the reactor equal to the vector sum of the charging currents of the two sound phases. The authors have used the proper capacitance in their calculations and it is only the statement in the early part of the paper that I feel needs modification.

The second comment I have applies to the discussion of overvoltages under fundamental frequency conditions. While I agree that on an extensive Petersen-coil system the voltage at points remote from the fault may exceed line-to-line voltage, I think it should be made clear that the type of voltage rise the authors discuss is not peculiar to a Petersen-coil system. The effect is the well-known tendency of a long line, energized to ground at the sending end and open at the receiving end, to show a rise in voltage at the open end. If the effect is sufficiently large in the case of a Petersen coil installation to require attention, it would also probably require attention if the same system were grounded at the same point in any other manner. For example, if the system were solidly grounded at one point only, the voltage rise at points remote from the ground might be sufficient to prevent its being treated as a solidly grounded system. In this conection it is interesting to note the tendency of a Petersen coil to establish, at the point of fault, line-to-ground voltages on the two sound phases which are equal to each other and no greater than line-to-line voltage, a condition which other types of neutral impedance may fail to accomplish. Figure 4, prepared for the system assumed in part II of the paper, illustrates the point I wish to make. At the upper left is indicated a neutral resistance grounded system. If, for the sake of convenience, we assume that the neutral remains fixed and allow the point representing the earth to shift with varying voltage drop through the resistor, we can conveniently represent the variation in the line-to-ground voltages of the sound phases. As the neutral resistance is varied, the point representing the earth moves along the circular locus in the diagram in the lower left, and the potentials to the sound phases are measured from the point on the arc corresponding to the value of resistance for which the voltages are desired. This diagram shows quite clearly that with neutral resistance grounding, the line-to-ground voltages of the sound phases are unequal and one of them may considerably exceed the line-to-line voltages, as in the case of phase-C voltage when the neutral resistance is 125 ohms. In the right half of this figure are shown the corresponding diagrams for reactance grounding. It is seen here that as the reactance increases, the locus for the "earth" remains very close to the vector E_A and that the line voltages do not depart very much from balance. In the particular example, the actual departure is even less than shown by the diagram which was distorted somewhat for the sake of clarity. In some types of systems, however, the unbalance may be considerably greater. It is seen that as the value of reactance approaches that required for a Petersen coil, the unbalance tends to decrease, and when it is at the value corresponding to the Petersen coil the line-to-ground voltages are essentially balanced and equal to line-to-line voltage. This is an effect typical of the Petersen coil, and except as propagation effects on long lines may come into play, Petersen coils tend, under fault conditions, to maintain line-to-ground voltage on sound phases substantially equal to line-to-line voltage.



A—RESISTANCE GROUNDING B—REACTANCE GROUNDING

Figure 4. Neutral grounding devices

S. B. Griscom (nonmember; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors have presented very interesting papers on operating features and computation of Petersen coils. In part I, under "Effect of System Operation," some of the pros and cons concerning the application of coils are given. It seems to me that under this heading a few other factors should be pointed out. One of these for lack of a better term will be called "adaptability to interconnection." Power systems having various types of grounding (solid, resistance, or reactance) may be metallically connected together with but slight changes in the relaying in the vicinity of the tie-in point. With a Petersen-coil-equipped system, however, it is necessary that both systems be equipped with the coils, or else use isolating transformers or their equivalent in making the connection. Thus, all new additions to the system or future interconnections may require the installation of additional equipment. The desirability for Petersen coils should also be considered in relation to the fact that American practice usually provides multiple feeds to important loads to insure continuity not only for transitory but also prolonged faults in case of physical line trouble. The trend toward higher relay and breaker speeds has greatly minimized the shock to the system for faults. A ground fault, unless very close to a full capacity solidly grounded transformer is inherently less severe than a phase-to-phase fault, and very much less severe than a three-phase fault, and the latter must be provided for in any case.

The information given under "Accuracy of Computations," part II, is very interesting. In view of the observed fact that calculated admittances are always lower than test data, I am wondering whether the authors have been able to trace this discrepancy to any commonly neglected factors, such as capacitance of insulator strings, height of vegetation, etc. I understand that in some cases, systems operating Petersen coils have found it necessary to change the compensation due to growth of corn, or the occurrence of a heavy snowfall. In the latter case it would appear more likely that snow or sleet on the conductors would be more effective in changing the zero-sequence capacitance, than a nominal depth of snow on the ground. The writer would like to ask whether any such effect has been noticed on the portion of the Consumers Power 140-kv system that is Petersen-coil equipped.

W. C. Champe and F. Von Voigtlander: Mr. A. W. Gothberg has suggested the use of a suitable grounded gap to bridge the insulator of the top conductor of a wood-pole line so that this conductor would act to shield the other two from high induced potentials. The resulting single-phase fault to ground of the combination conductor and shield wire, when discharging a high potential, would be cleared by the Petersen coil. A similar plan has been advanced by the authors and others, and also the possibility of reducing the insulation of the top conductor on steel tower lines without ground wires has been considered on systems equipped with Petersen coils. Though the authors have not had the opportunity of observing such schemes in actual use, it would appear that they would be rather successful in reducing line outages due to lightning and that they would greatly extend the field of usefulness of Petersen coils.

While on highly insulated wood-pole lines, lightning outages may be predominantly phase-to-phase faults, the fact still remains that there are thousands of miles of moderate voltage wood-pole lines in this country on which transitory ground faults are an appreciable proportion of the total faults experienced. This ratio of transitory ground faults to total faults becomes an important criterion for successful Petersen-coil installation. A ratio of transitory ground faults to total faults of as high as 50 per cent is not at all uncommon, particularly on lines of older construction. On such lines Petersen coils have proved eminently effective.

Mr. Griscom has suggested a factor aptly called by him "Adaptability to Interconnection," which is an important consideration in the application of Petersen coils to systems which may be switched onto other systems not so equipped. Where it is necessary to switch a Petersen-coil-equipped system onto such other systems, the switching must be done through transformers having a high zero-sequence impedance, if the effectiveness of the Petersen coils are to be retained, unless the interconnected system is non-grounded and is within the tuning range of the coils.

Mr. Griscom asked regarding the effect of the height of vegetation, increased conductor diameter due to snow or sleet, occurrence of heavy snowfalls, etc., on the tuning of the Consumers Power Company's 140-kv Petersen-coil system. While these factors have an effect on the system admittance to ground, such effects have not been observed to an extent sufficient to warrant retuning of the coils.

Messrs. Griscom, Hunter, and Lewis have commented on the accuracy of computations and on the fact that the observed values of system admittance to ground have always been found to be greater than calculated values. From the tests and calculations which have been made, the effects of height of vegetation, capacitance of insulator strings, etc., have not been found to be sufficient to account for these differences between observed and calculated admittances.

In the authors' experience, the quadrature components of fault current have been consistently predicted within ten per cent of measured values. In such calculations, the system admittances have been increased ten per cent above the values computed by standard methods, since, as pointed out in the paper, the authors have found the measured values to be consistently ten per cent greater than those calculated on the systems with which they are familiar. In the example in the paper, this ten per cent increase in admittance was not made, as experience on other systems may show a somewhat different relation between measured and calculated admittance. The quadrature component of fault current was calculated in the example as 34 amperes. With the admittance increased ten per cent this current component becomes 38 amperes, which could be expected to be within ten per cent of the measured value on the basis of the authors' experience and about 13 per cent on the basis of Mr. Hunter's experience. The discrepancy between the measured and calculated total ground fault current in the Colorado example cited by Mr. Lewis can probably be ascribed to the magnitude of the in-phase components, since the measured and calculated quadrature components checked quite well. It is hoped that further investigation into the differences between calculated and measured values of line admittances will be made and that the results of such investigations will be made available to members of the Institute. As observed in the paper, the computation of the in-phase components is subject to large error, especially for the smaller values, as the effect of the intangibles on the magnitude of these components then becomes larger than the effect of the system resistances.

Messrs. Hardaway and Hunter have discussed the magnitudes of the in-phase components of fault current on operating Petersen-coil systems. Mr. Hardaway reports in-phase fault current arcs of from 20 to 25 amperes are being cleared without difficulty on the Colorado 100-kv system, and points out that fault currents of from 40 to 50 amperes are being interrupted on the Michigan 140-kv system. The maximum values of in-phase component of ground fault current which can be tolerated for a given system equipped with Petersen coils has not been even approximately established, to the authors' knowledge. Experience has shown that in-phase transitory arcs up to 50 amperes are generally successfully extinguished, though during quiet conditions, such arcs have been known to continue for over 800 cycles. Wind and weather conditions have a very important effect on the behavior of arcs of this sort, and in any test to determine the range of maximum current which can be extinguished wind and weather conditions would have to be considered.

Tests have been made on long and extensive medium-voltage systems where the resistance to reactance ratio was high but corona was no factor, in which sufficiently large in-phase currents were measured to make questionable the successful operation of Petersen coils. On extensive high-voltage systems where corona was present, in-phase components as high as 160 amperes have been calculated. However, in the majority of systems encountered in practice, particularly at voltages under 66 kv, the in-phase components are probably of only secondary importance.

Messrs. Hunter and Jeanne made some very interesting comparisons of system voltages to ground for isolated-neutral, grounded-neutral, and Petersen-coil-equipped systems. In Mr. Hunter's tabulation it is interesting to note for the case of the isolated neutral that as the number of generators on the system is reduced from three to one, the positive- and negative-phase-sequence impedances of the system increase to a point where they are of appreciable magnitude compared to the zero-sequence impedance, resulting in considerably higher system voltages to ground. Incidentally phase-to-phase voltages would also be found to be considerably higher than normal for the assumed ground-fault conditions.

Mr. Hunter asked for the authors' further comment on the high transient overvoltages coincident with line-to-ground faults. The authors believe these transients to be of the nature of switching surges, due largely to the rearrangement of line capacitances to ground incident to the occurrence of the fault. As Mr. Hunter observed, these transients are of too short duration to be accurately recorded on conventional magnetic oscillographs. The authors have not carried out any extensive investigation of these transients, either mathematically or in tests, but have observed what magnitudes may be experienced by the use of surge recorders or klydonographs on systems during ground-fault tests. Such values as have been observed, though of surprising magnitude, have been found to be well within the limits of insulation strength of connected apparatus and equipment. No doubt these transients also are mitigated by the Petersen coils.

Mr. Jeanne observed that the reactance of Petersen coils is determined from the direct capacitance to ground of all three phases of a system, and not from that of only the two unfaulted conductors as might be inferred from the paper. The authors of course agree with this, having the point in mind, as Mr. Jeanne mentioned, that the coil current is equal to the quadrature component of the charging current of the two unfaulted conductors. Mr. Jeanne's discussion and diagrams of these relations and the effect of neutral resistance and reactance on the system voltages to ground are very interesting. They demonstrate the points in question very well, and are worthy of detailed study by everyone interested in this subject.

The empirical relations which Mr. Lewis has shown between the calculated charging current and the measured Petersen-coil current, and the relations between the calculated capacitance to neutral and the zero-sequence capacitance are based on a very wide experience in this field and on a considerable number of tests. They should, therefore, be a useful guide in working out these values for any given power system.

The authors agree with Messrs. Rankin and Neidig regarding the use of lightning arresters rated at less than line-to-line voltage on Petersen-coil systems. However, there appears to be some misinterpretation on the matter of permissible lightning-arrester ratings, as the point intended in the paper was that multiple Petersen coils may permit the use of lightning arresters with a rating lower than those which might be used for a totally isolated system. That is, on a totally isolated neutral system, certain of the lightning arresters might well be required to have ratings considerably in excess of that based on normal line-to-line voltage, whereas on a system equipped with multiple Petersen coils, the rating based on normal line-to-line voltage would probably be adequate. For example, normally on a 33-kv isolated-neutral system, 37-kv ligntning arresters would be used. However, if it were a large and extensive system, 43-kv arresters might be required at some stations to interrupt high dynamic overvoltages. If this system were equipped with only one Petersen coil, a number of the 43-kv arresters might still be required, but if it were equipped with multiple Petersen coils, the use of 37-kv arresters might well be feasible throughout.

It is presumed that the maximum recorded voltages mentioned as never having been found to exceed 1.7 times normal line neutral voltage, refer to a system equipped with multiple Petersen coils.

Transpositions are of considerable importance in a Petersen coil application, as their proper use reduces the normal residual voltage of the system and thereby limits the continual current through the coils and restricts neutral displacement during normal system conditions.

The number of coils required on a system would be a function of the possible sectionalized operation of the system. Whether or not all grounding transformers should be equipped with Petersen coils would be a matter for individual engineering judgment on the system involved.

Since there is but little maintenance work to be done in connection with Petersen coils, it would appear difficult to justify any but the simplest means of by-passing the coil and grounding the neutral. Justification for additional equipment would depend largely on local conditions.

The comments of Messrs. Rankin and Neidig on the results of operation with a 66-kv system equipped with three Petersen coils show the effectiveness of this installation. The results which have been obtained with as much as 25 per cent of the system for which the coils were tuned, disconnected without retuning the coils are interesting, particularly as all cases of faults were successfully cleared in comparatively short times.

In closing, the authors extend their appreciation for the many interesting discussions of this paper that were submitted.

The Fundamental Principles of Fluorescence

By GORTON R. FONDA
NONMEMBER AIEE

FLUORESCENCE is a property of many substances. It consists of an emission of light under excitation by radiation whose wave length falls within a critical absorption band. When the emission persists for an appreciable period after the existing radiation has been extinguished, it is known as phosphorescence.

At a low order of brightness fluorescence is encountered in a great number of the organic products of our daily life, such as seeds, plants, woods, eggs, milk products, lubricating oils, print and paper. Their emission exhibits characteristic features that make it possible to determine variations in quality and type.[1] Indeed, fluorescence has even been developed as a tool in microchemical analysis for the detection and estimation of several of the metals as well as of many organic compounds.[2] It appears also among many minerals. Especial interest, however, attaches to artificially prepared products. They include solutions, both liquid and solid, and also solid inorganic substances, such as sulfides, oxides, tungstates, and silicates. Fluorescent solids are generally known as "phosphors."

There are two striking characteristics that one notes in surveying the artificial products. One notices first that fluorescence is frequently associated with the presence of a foreign ingredient at a very low concentration. In inorganic phosphors this foreign ingredient is an appropriate metal at a concentration of one per cent or less. In organic dye solutions, which may be either liquid or solid, it is a dye at a concentration much less than one per cent, with the further limitation that that dye shall be one of a few whose selection depends upon the presence in its molecule of certain derivatives of benzene.

This peculiarity of fluorescence associated with the presence of a specific ingredient at low concentration suggests an analogy with the behavior of a vapor or gas at low pressure within an enclosing tube. In both cases luminescence results by illumination with the light of a critical wave length, and in both cases the luminescence formed decreases in intensity as the concentration of the effective element is raised, whether it be a foreign ingredient in a solid or the pressure of gas in a tube. In the case of a gas the phenomenon is known as "resonance radiation." The illumination exciting it must have a wave length corresponding to an absorption band of the gas. In this way it induces resonance in the atoms or molecules of the gas, exciting them to such an extent through the absorption of energy that an electron is driven out to an outer orbit. The condition for this is that

$$E = h\nu$$

where E is the energy of a quantum of the exciting radiation, and ν is the frequency corresponding to the wave length at which energy can be absorbed to excite the atom to resonance. The luminescence arises from the return of the excited electron to its normal orbit, and this return is accompanied by an emission of energy of the same frequency. Consequently, the luminescence is of the same wave length as that of the exciting radiation.

The condition in a phosphor is more complex because the basic substance, whether solid or liquid, is itself made up of atomic groups at a relatively high concentration, and completely enveloping the scattered, occasional particles of the active ingredient. This characteristic, however, is so far from breaking the analogy with resonance radiation in a gas at very low pressure that it actually serves to strengthen it by acting as basis for an explanation of the one outstanding difference between the two. The explanation is derived from the second observation that becomes apparent to the investigator in his endeavor to pick out the salient features of fluorescence. It is the fact that the fluorescence is not monochromatic, as that of the exciting radiation may be, but extends over a broad band of the spectrum and, in general, is displaced to a position of longer wave length than that of the exciting radiation. This latter characteristic is known as Stokes' Law.

A survey of some characteristic features of resonance radiation will serve to bridge the gap between it and fluorescence, and to demonstrate the basis for the transition to the condition described by Stokes' Law.

The simplest case is that of pure sodium vapor at very low concentration—so low in fact that the time during which an electron stays in an excited state shall be less than the time between collision of the excited atom with some neighboring atom. The luminescence of sodium vapor, such as is exhibited in the sodium lamp, is made up of the D-line doublet, 5,890 angstrom units and 5,896 angstrom units. The emission of this doublet, as illustrated in figure 1, is the result of the return of excited electrons from two energy levels lying close together, the $2^2P_{1/2}$ and the $2^2P_{3/2}$, to the lower normal level $1^2S_{1/2}$. When the vapor is sufficiently low in pressure, only one of these lines can be excited as resonance radiation by the absorption of light of corresponding wave length. This is as theory would predict. When, however, the pressure is raised to 0.015 millimeters, corresponding to a temperature of 300 degrees centigrade, or when a fraction of a millimeter of hydrogen is introduced, both lines appear, even though the exciting radiation is limited to one line. This is due to a collision of some of the excited atoms with neighboring atoms. Such a shock leads to an energy transfer sufficient to throw the excited electron into the closely adjacent energy level, for the energy difference between the two states yielding the doublet corresponds to only 0.01 volt. The result illustrates for a system as simple as sodium vapor how sensitive the character of its radiation is to the influence exerted by neighboring atoms upon one another, even while at a relatively low concentration.

The condition becomes more complex for a vapor such as iodine which is in the molecular rather than the atomic state. In iodine vapor the two atoms constituting the diatomic molecule are free to vibrate back and forth with respect to one another, making various vibrational energy states possible. Furthermore, the

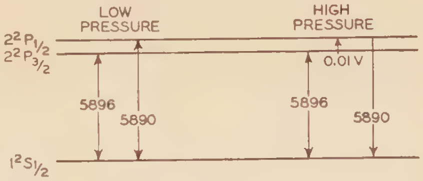


Figure 1. Energy-level diagram for resonance radiation of sodium vapor

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1. For all numbered references, see list at end of paper.

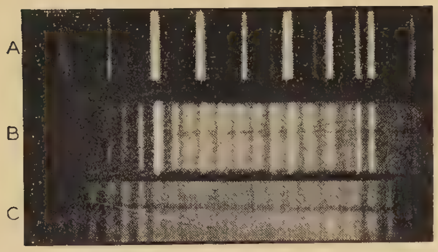

Figure 2. Resonance spectrum of iodine vapor, as affected by presence of helium (From R. W. Wood and J. Franck, Verh. d. D. Phys. Ges., 13, 85, 1911)

A—No helium
B—Two millimeters of helium
C—Ten millimeters of helium

molecule can rotate about the axis uniting its two atoms, thus giving rise also to various states of rotational energy. Consequently, there are not only the usual number of electronic energy levels, but each one of these levels is subdivided into additional ones corresponding to the possible vibrational energy states, and each one of these is subdivided again into a series of rotational energy levels. For iodine vapor the case is rendered so complex by these features that its pure resonance spectrum no longer consists of a single line but of a succession of doublets.

A more significant feature, however, is shown by an increase in pressure sufficient to lead to collision of excited iodine molecules with neighboring molecules. The resulting energy interchange is such as to shift the excited electrons to adjacent vibrational and rotational states. Consequently, when the electrons return to their normal orbit, it will no longer be by a succession of definite, specific jumps, leading to an emission of clear-cut doublets, but rather by jumps of variable magnitude, the energy of each of which is determined by that of the abnormal excited state attained in the collision. These states are so close together that the resulting emission can no longer be resolved into lines, but appears as continuous radiation arranged as bands at the location of the expected doublet. There is still another effect associated with high pressure. As the result of collision, the excited electron itself loses energy on its return to the normal orbit, leaving a smaller amount available for emission as light. Consequently, the emission is displaced toward the red. Both of these effects, so characteristic of fluorescence, the broadening of the emitted radiation and its displacement toward the red, were produced in the resonance spectrum of iodine vapor by the introduction of helium, as well as by increases in the vapor pressure of the iodine,[3] as shown in the photographs of figure 2.

These observations on resonance radiation illustrate how complications arise even in the gaseous state, as one passes from a monatomic to a diatomic vapor and from very low pressures to pressures of a few millimeters. It can, therefore, be readily comprehended that, as the concentration of atoms and molecules is still further increased to such a point that their condition becomes that of a liquid or a solid, the mutual interplay of forces between them will become much more intricate and involved, and their effect still more pronounced on the character of the emitted light. The theoretical development in recent years has, in fact, shown that the energy states in a solid can no longer be represented by a few lines of discrete energy values, as in a monatomic gas at low pressure, or even by large groups of lines corresponding to the vibrational and rotational states of a diatomic gas. The interplay of forces between atoms as contiguous as in a solid is so manifold that each group of electronic levels becomes packed with many lines and develops into what is virtually a continuous band of energy. This condition is illustrated in figure 3 by contrast with that for a vapor already brought out in figure 1. A detailed discussion of the situation is given in a recent review by Seitz and Johnson.[4]

In figure 3 two such bands are shown. The lower one represents the outermost energy state under normal, unexcited conditions. The upper is referred to as a "normally empty band." It represents the energy state into which an electron would be driven if excitation could occur. In solids which are insulators at room temperature, the bands are so far apart in energy content that the available processes for excitation are insufficient to raise an electron from the filled band to the upper unfilled one. The case becomes different, however, if in some way a localized state may be inserted between the two bands. Such a condition is produced for instance when a small amount of an impurity is dissolved in the crystal. Some of the energy states of this impurity will of course fall within the normal banded levels of the solid, but under appropriate choice the uppermost filled level of the impurity will appear as a discrete, localized state, lying above the filled band of the crystal, as shown in figure 3. Its position with reference to the upper unfilled band of the solid, can be assumed to be such as to allow of excitation under radiation of appropriate wave length, causing an electron to make the jump from this localized level into the unfilled band. The consequence will be that an emission of fluorescence will occur, associated purely with this impurity atom. The excited electron will descend by a series of thermal interchanges to the bottom of the unfilled band. Consequently, the energy emitted by its return from this point to its normal state will be lower than the energy of excitation, and the resulting fluorescence will be displaced toward longer wave lengths.

Complicating features due to the proximity of neighboring atoms of the solid have the effect of broadening the emission into a band. The cause of this effect, as well as the extention to longer wave length, can be more clearly discerned by consideration of the Franck-Condon Principle.

In the diagram of figure 4 the abscissae denote the distance between an atom of the foreign metal and, for simplicity's sake, one of its neighbors. Due to thermal vibrations and under the alternate forces of attraction and repulsion, the distance between the atoms will vary periodically so that the potential energy may be represented by the ordinates of the two curves, *N* for the normal condition of the metal atom, and *E* for its excited state. Consider that the vibra-

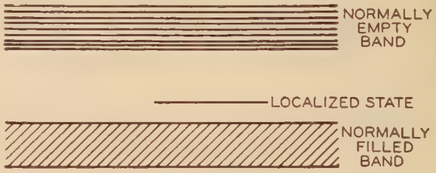

Figure 3. Energy bands for a solid

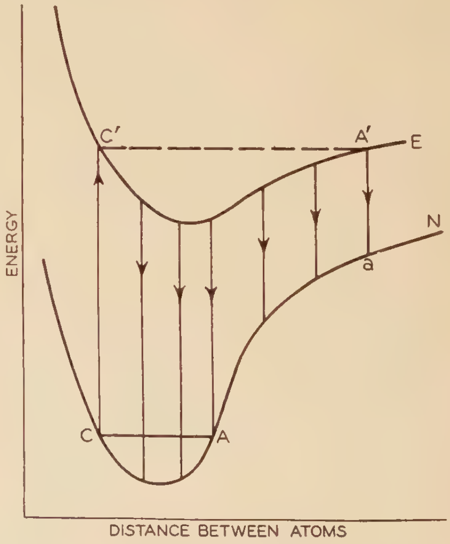

Figure 4. Excitation and emission of a phosphor according to Franck-Condon Principle

Table I. Fluorescence of Rhodamine B at Various Concentrations in Cellulose Acetate Films

Molar Concentration	Peak Wave Length Fluorescence (Angstrom Units)	Yield of Fluorescence (Per Cent of Radiant Energy)
$4(10)^{-6}$	5,900	5.4
$4(10)^{-5}$	5,930	28.3
$4(10)^{-4}$	6,050	44.0
$4(10)^{-3}$	6,210	4.6
$3(10)^{-2}$	6,250	1.0

tion is such as to lead to maximum oscillations between the points *C* and *A*. The Franck-Condon Principle prescribes that the time of excitation is so short as compared with the time of vibration that a transition from the lower to the upper level will take place along a vertical line, such as *CC′*. While in the excited state vibrations will continue between points of equal potential energy, such as *C′* and *A′*. As the duration of the excited state persists over a finite time, the return of the electron to its normal position may be represented as occuring from any position along the curve *E* between the points *C′* and *A′*. It is an inherent feature of the Franck-Condon Principle that the curves *E* and *N* shall have the different shapes shown in figure 4 as representative of the difference in the interplay of forces between an atom and its neighbors, depending upon whether the atom is in the normal or excited state. Consequently, the energy emitted by the return of the electron will not be equal to the energy of excitation, represented by the line *CC′*, but will have a succession of lower energy values depending upon the point on curve *E* from which its return starts and extending as low as the transition *A′a*. Such a process would therefore yield a continuous band of emitted fluorescence extending to longer wave lengths than that of the exciting monochromatic radiation. This viewpoint has been given quantitative treatment by Seitz[5] for the case of the halide phosphors, developed experimentally by the school of Pohl and Gudden.[6]

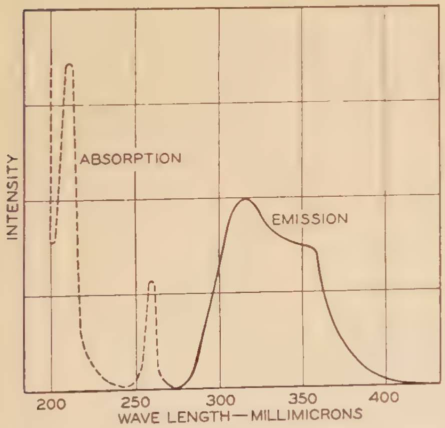

Figure 5. Absorption and emission spectra of potassium bromide activated with 0.003 per cent thallium (From W. von Meyeren, Z. Phys., 61, 321, 1930)

It has been convenient to visualize the localized state as one induced by the presence of an impurity atom. It is conceivable, however, that it might be realized in other ways leading to irregularities in the lattice, such as by departures from stoichiometric proportions in the composition of the solid, by a low concentration of an allotropic form of the solid, by the dispersion of the active molecules in a solution, or by their adsorption in dispersed form on a solid. In the discussion that follows of various types of fluorescence, the question is to be kept always in mind—what is the feature that serves as source of fluorescence by introducing a foreign condition into a solid or liquid?

Fluorescent Organic Bodies

There are many organic compounds which exhibit a low fluorescence. Benzene can be taken as an example. As a vapor it can be excited by illumination to yield a purely resonance radiation, also termed fluorescence, consisting of a succession of narrow bands arranged in groups. At closer proximity of its molecules, such as in the solid or liquid condition at zero degrees centigrade or in solution in alcohol, the subsidiary bands of a group agglomerate into a broad band, and these bands become displaced toward longer wave lengths, a trend that becomes still more pronounced as the concentration of a solution is increased. The same observation has been made for all aromatic substances studied, as well as for benzene, namely, that the fluorescence bands are displaced to longer wave lengths as the physical state is changed from a vapor to a liquid or solid solution.[7] The results serve again to illustrate the transition from pure resonance radiation to fluorescence, involving the broadening of bands and the shift in wave length that are consequences of slight increases in concentration. In this type of substance the active group seems to be the molecule itself of the compound, for the fluorescence is virtually extinguished at such high concentrations as are present in a pure liquid. It appears at its best in dilute solutions or in an adsorbed film at high dispersion on cellulose or silk fibers. Variations in the character of this type of fluorescence have been particularly applied by Haittinger to a system of organic analysis.[2]

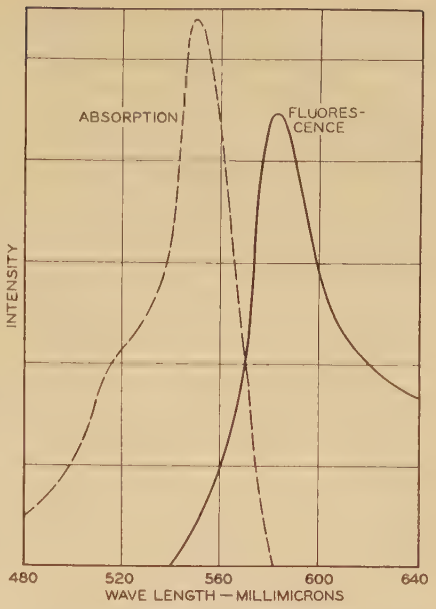

Figure 6. Absorption and fluorescence spectra of rhodamine in alcohol solution (From A. Poristky, Journ. Frankl. Inst., 197, 527, 1924)

A much higher intensity of fluorescence is exhibited by certain of the organic dyes. It appears only in liquid and solid solutions, and is completely absent in the pure, solid dye. Rhodamine can be taken as a typical example, especially because it was one of the first to be considered for commercial application in fluorescence from a proposal made by Cooper-Hewitt.[8] Its fluorescence can be excited by the ultraviolet, but is more generally excited through radiation with green light lying within the range of its absorption band. The relation between this band and the fluorescence is brought out in figure 6. Each is seen to be roughly the mirror image of the other. The full fluorescent spectrum is excited by any wave length lying within the absorption spectrum.[9] As the concentration of the solution is increased, the band of fluorescence passes through an optimum in intensity and at the same time is displaced toward the red, as brought out in table I for films of rhodamine *B* in cellulose acetate excited by the mercury green line.[10] The concentrations given apply to the alcoholic solution before evaporation to yield the solid film.

The existence of an optimum intensity of fluorescence at a critical concentration has been found to be a characteristic common to the solutions of all such dyes and to fit the Brunighaus equation[11] $I = kce^{-Bc}$, where I denotes the intensity of fluorescence and c the dye concentration. The decrease in fluorescence beyond the optimum value is presumably due to the increase in probability of collision between excited and normal dye molecules.

The energy of an excited molecule may of course be dissipated by collision with any molecules capable of resonating with it. This influence is shown by a wrong choice of solvent, which either lowers the fluorescence or destroys it utterly.[10,12] It is also shown by the addition of certain foreign materials which reduce the fluorescence even though they are chemically inert.[7,13]

At the optimum concentration of rhodamine, as shown in table I, the efficiency of conversion of the mercury green line into fluorescent energy corresponds to the production of one quantum of fluorescent energy by the action of 1.6 quanta of absorbed energy, a conversion that is approaching closely that which would be theoretically attainable.

Fluorescent Inorganic Substances Containing Metallic Activators

Mention has already been made of the alkaline halide phosphors developed by the school of Pohl and Gudden.[6] Fluorescence is absent in the pure halides but appears when a trace of thallium is introduced. The characteristics are presented in the curves of figure 5 for the typical case of potassium bromide. The presence of the thallium gives rise to two new absorption bands. Fluorescence is excited by radiation of any wave length lying within these bands. It seems clear therefore that the fluorescence arises from excitation of the thallium, and the theoretical treatment by Seitz[5] furnishes a quantitative basis for this conclusion.

In the experiments described the amount of thallium in the halides was limited to very small concentrations that would not interfere with the formation of single crystals. The writer has investigated the effect of larger amounts in microcrystals. In general an optimum concentration was found, as is brought out in table II for the case of caesium iodide excited by the mercury line 2,536 angstrom units.

The dependence of fluorescence upon the presence of a foreign metal at low concentration is exhibited in other inorganic materials. For the alkaline earth sulfides and zinc sulfide, extensively investigated by the school of Lenard,[14] these activators include manganese, copper, silver, antimony, lead, and bismuth. The pure sulfides, with the possible exception of zinc sulfide, are devoid of fluorescence in the absence of an activator. The color of their fluorescence varies with the activator used. The fluorescence increases to an optimum value at a critical concentration of the foreign metal and decreases to extinction at higher concentrations, just as for the halides.

Many of the oxides also may be made fluorescent by addition of a foreign metal. Calcium oxide is a typical case. It is activated by manganese, copper, lead, bismuth, and antimony, each yielding a different color. In the extensive investigation by Ewles[15] an optimum concentration was found for each of the last three metals.

The existence of an optimum content of a foreign metal in these diverse types of inorganic compounds is obviously related to the effect of an optimum concentration in solutions of dyes. The fact that the fluorescence reaches a saturated value and then decreases for larger amounts of the metal signifies again that an activated atom can lose its energy when a neighboring atom of the metal approaches it too closely. Unpublished observations by the writer on related effects indicate that this loss is due to the thermal vibrations of the atoms, and that its extent depends upon the amplitude of these vibrations.

Manganese finds very extensive use as an activator. Besides the sulfides and oxides, it has been found also to activate certain sulfates, phosphates, and silicates.[16] In the case of zinc silicate, the writer has found that the fluorescence is displaced toward the red as the concentration of manganese is increased, as brought out in table III.

This result is important in that it demonstrates that the same effect is observable in the fluorescence of inorganic solids as in that of organic solutions and in the resonance radiation of vapors—namely, a shift in the emitted radiation to longer wave lengths that accompanies an increase in concentration of the active ingredient.

A natural query arises as to the condition in which the foreign metal activator is incorporated in the basic substance. Experiments by the writer on X-ray analysis of zinc silicate phosphors have demonstrated that manganese atoms enter into the crystal as integral parts by substitution for occasional zinc atoms. The result is a slight extension in lattice spacing, due to the larger size of the manganese ion, as compared with the zinc.

In a different way Riehl has arrived at the same conclusion for zinc sulfide activated with copper.[17] The crystals of the phosphor were treated with hydrochloric acid so as to dissolve them slowly. As they became smaller, however, the fluorescence characteristic of copper activation continued and persisted almost up to complete solution. This is direct evidence that the copper had penetrated the lattice rather than formed as an adsorbed layer on the surface.

Table II. Fluorescence of Caesium Iodide Activated With Various Percentages of Thallium

Percentages of Thallium by Weight	Relative Fluorescence
0.07	88
0.22	100
0.37	84
1.11	39
8.70	5

Table III. Effect of Manganese Concentration Upon the Color of Fluorescence in Zinc Silicate Phosphors

Percentage of Manganese	Peak in Fluorescence (Angstrom Units)
0.1	5,270
0.4	5,280
0.9	5,290
1.4	5,310
2.3	5,330
4.5	5,350

There are many natural minerals that fluoresce, one of the most notable being a variety of willemite from New Jersey known as Franklinite. So far as these minerals have been investigated, they have been found to contain a foreign metal impurity as source of the fluorescence.[7]

The fluorescent glasses fall in this same classification, for their luminescence under radiation is due to activation by a foreign metal at very low concentration. It may be uranium or even one of the common metals such as manganese.[18]

Fluorescent Inorganic Salts Free of Metallic Activators

In this class there are several types of salts whose fluorescence has been found to be due to the presence of an abnormality, again at low concentrations. It may be a foreign acid radical. The fluorescence in bone and teeth, for instance, seems to be associated with the presence of about two per cent of an organic compound, for it disappears when they are fired at 600 degrees centigrade. Furthermore, it can be produced artificially by the incorporation in calcium phosphate of a small amount of an organic product.[19] Doctor Byler of this laboratory [General Electric Company, Schenectady, N. Y.] has just shown that the fluorescence of calcium phosphate may also be induced by incorporating a critical amount of the acid phosphate in the hydroxy phosphate, and that similar complex salts of other metals can be formed at such critical compositions that fluorescence results.[20]

A related case is that of zinc carbonate which developed fluorescence when it had been fired sufficiently to bring about partial decomposition into the oxide. An optimum fluorescence resulted at a composition of 11 molar per cent zinc oxide combined with 89 molar per cent zinc carbonate.[21]

Still another type of abnormality is represented by the presence in a salt of a small amount of an allotropic modification of that same salt. Doctor Byler developed fluorescence in barium chloride, for instance, by firing it for a short time just above its transition point. Another instance is furnished by the long controversy over the fluorescence of zinc sulfide. The variations in the intensity and color of its fluorescence that have been produced by altering the amount and kind of a foreign metal impurity demonstrate that activation of zinc sulfide by a foreign metal actually exists. However, a low degree of blue fluorescence arises on firing zinc sulfide to which no metallic impurity has consciously been added. There is a suspicion that this arises from the presence of a residual impurity which the chemical purification has not been capable of removing. Schleede, however, has demonstrated that the fluorescence of the purported pure zinc sulfide is at a maximum after a brief firing at 1,000 degrees centigrade, which served to convert a part of it from the cubic to the hexagonal form. He concluded that the fluorescence arose from this intermixture of different crystalline types, for it disappeared under slightly higher firing at temperatures most suitable for the development of fluorescence in the presence of foreign metals.[22] He ascribed the loss in fluorescence of the pure sulfide at such temperatures to its complete conversion to the hexagonal form.

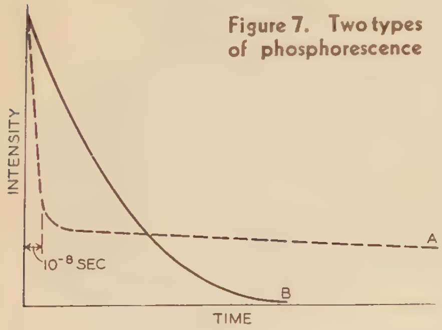

Figure 7. Two types of phosphorescence

There are many metals which can be identified by the fluorescence of their salts, most especially those with certain organic acids. In general, however, this fluorescence is observed as adsorbed films on a suitable base, such as filter paper, or in solution. It would seem to be due, therefore, to a fluorescence of the molecule under the condition of sufficient dispersion to prevent disturbances by collision.[2]

There are, however, other cases in which fluorescence is associated with pure inorganic solids which are not yet known to contain any abnormalities. Such are the salts of the rare earths and of the uranyl radical and also the tungstates and molybdates.[14] It is reasonable to expect that the presence of some abnormality will eventually be found in them also.

Phosphorescence

The light emitted during radiation by the exciting source is known as fluorescence. In many cases the fluorescent substance continues to emit light after the exciting source is extinguished. Such a delayed emission of light is known as phosphorescence. The two are intimately related as manifestation of the same fundamental phenomenon, namely, excitation of an atom. When the excited electron returns directly to its normal orbit, simply fluorescence is observed as the result of what Lenard calls an instantaneous process. When, however, the return of the electron is for any reason delayed, thus giving rise to phosphorescence, then, by way of distinction, Lenard refers to it as the result of a delay process.

Actually fluorescence may persist for an instant, of the order of 10^{-8} second, after the exciting source is extinguished. When no luminescence beyond this period is observed, then one can be assured that the instantaneous process is the only one involved. When phosphorescence is manifested, however, it is clear that both processes are going on simultaneously during direct illumination. Their relative proportions in two different phosphors can be estimated by measuring the rates at which their phosphorescence decays after extinction of the exciting light. If one substance shows a sharp initial decay, less than about 10^{-8} second, such as that represented by the first portion of curve *A* in figure 7, to be followed by a slow decay which begins at low intensity, then it is clear that the light emitted from it during illumination is produced to a relatively greater extent by the instantaneous process.

The delay process itself is characterized by differences in the speed with which it is carried out. This is manifested by differences in the character of the decay curve. In figure 7, for instance, even though the delay process is predominant in *B*, yet the speed of its decay is relatively so high that its phosphorescence has fallen to zero at a time when the longer life phosphorescence from *A* is still observable.

In the case of a sulfide phosphor, there are generally three different types of phosphorescence, each excited by a narrow band of differing spectral distribution The instantaneous process giving rise to fluorescence is excited by a broad band whose spectral distribution includes all of the narrower bands which lead to phosphorescence. The halides offer a contrasting case. In them there are two distinct absorption bands, as brought out in figure 5. Excitation by the one of longer wave length yields only fluorescence, whereas excitation in the shorter band leads to both fluorescence and phosphorescence as well.

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A Memory Attachment for Oscilloscopes

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ASSOCIATE AIEE

THE DEVICE described in this paper, called a "memnoscope," is a system for obtaining an oscillogram of random phenomena and events immediately preceding and following its occurrence.

This system was developed and has been used to study arc-back phenomena in mercury-arc rectifiers. Other methods, such as the use of long transmission lines and high-persistence cathode-ray tube screens[2] have been used to obtain oscillograms of random phenomena.

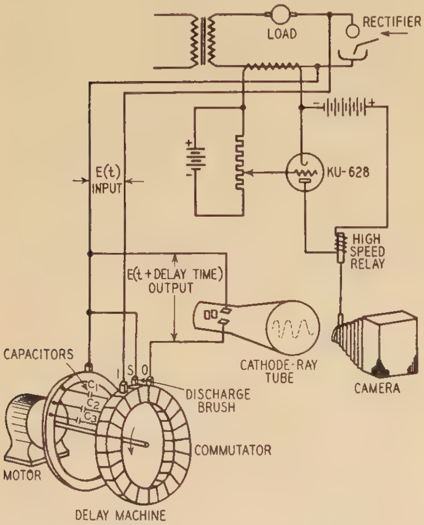


Figure 1. Memnoscope: A system for oscillograms of random events

It is possible to obtain volt-current-time data on one film because the discharge of each condenser element of the memnoscope gives a dot on the oscilloscope record and a knowledge of the commutator speed and number of condensers gives time (see figure 4*a*). Information on random transmission-line faults can be obtained from normal conditions, through fault time and back to normal.

Description of Complete System

In figure 1 is shown a rectifier which is a source of a random[1] occurrence commonly known as arc-back. If it is desired to obtain an oscillogram of conditions in a rectifier immediately preceding and following the arc-back, a system as shown in figure 1 can be used.

The grid of the thyratron is excited by the random phenomenon and the plate current opens the camera shutter. A picture is obtained of the motion of the spot on the cathode-ray-tube screen. Since the motion of the spot is determined by potentials of the rotating capacitors and if rotation is as shown in the figure, the picture taken will be of events occurring prior to the time the random phenomenon occurred. The heart of the system is the rotating capacitor network designated in figure 1 as "delay machine."

Construction of Delay Machine

To obtain satisfactory oscillograms at 60 cycles, for the conditions investigated, a machine with 147 capacitors was constructed. This machine was built using a standard commutator with 147 bars and 147 0.01-microfarad capacitors mounted around the shaft. One terminal of each capacitor was connected to a commutator segment; the other terminal was connected to a collector ring. The whole assembly was balanced and then mounted in a standard motor frame of suitable size. The size of the completed capacitor unit, which is the machine in the foreground, and the driving motor can be seen from figure 2. The capacitors are of the commercial paper-wax tubular type, $1/2$ inch in diameter and one inch long.

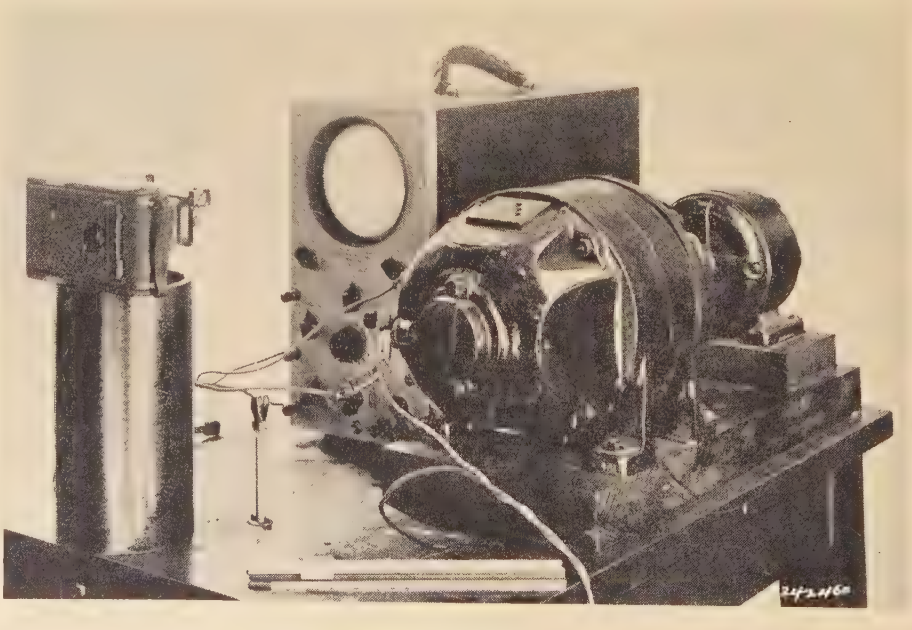
The brushes are mounted close together in order to utilize as many of the total number of capacitors as possible. With rotation as shown in figure 1, *I* is the input brush, *S* is the short-circuiting brush, and *O* is the output brush.

Operation of Machine

Assume the direction of rotation as shown in figure 1 and a voltage $E(t)$ across the input terminals. The resistance and inductance of the input circuit are negligible; then the capacitor, C_1, at the same time it leaves the brush *I* will be charged to a voltage $E(t_1)$. After a time very nearly $1/rps$ seconds (the delay time) this capacitor, C_1, will be under brush *O* and the voltage $E(t_1)$ can be recorded. Before C_1 can reach the input brush again, it is discharged by the short circuiting brush *S* bringing $E(t_1)$ to zero and C_1 is ready for another transfer of charge.

All the capacitors C_1, C_2, C_3, C_4 . . . . . . transfer their specific charges once per revolution and a stepped wave $E'(t)$ is obtained at the output end. This wave is $1/rps$ second behind the wave $E(t)$. The number of electrical degrees per step is $\theta = f/rps \times 360/b$. Where f = frequency and b = total number of capacitors in the machine. For 1,800 rpm and a 60-cycle wave θ = 4.90 degrees. This means that there will be 73.5 steps per cycle of a 60-cycle wave.

Figure 2. Apparatus as used to obtain pictures. The larger machine contains rotating capacitor network



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2. For all numbered references, see list at end of paper.

The delay time is that of one revolution of the commutator corrected for the total span for the three brushes. In this case it is $t_m = 1/rps \times 142/147 = 0.0322$ second for 1,800 rpm. This time is nearly two cycles of 60-cycle frequency.

Oscillograms, figure 4, have been obtained using a cathode-ray tube, with the output voltage connected directly to the plates. The input voltage required under these conditions is 50 volts for one-inch deflection on the cathode-ray-tube screen.

The machine can be used with the magnetic-type oscillograph if a suitable coupling means is used between the output of the machine and the oscillograph. By using more than one group of three brushes on the commutator, more than one picture can be taken at the same time. Also, more than one commutator can be mounted on the same shaft if more records are required.

Response Characteristics—Input End of Network

Equation 5 (see appendix) indicates that if a wave definition p (number of steps per cycle of highest frequency to be reproduced) is required, the RC product should be decreased as the frequency desired is increased. It is desirable to use as small a value of resistance in the input circuit as possible. If a resistance potentiometer is used to supply voltage to the network, the resistance of this input device is to be included in determining the frequency response.

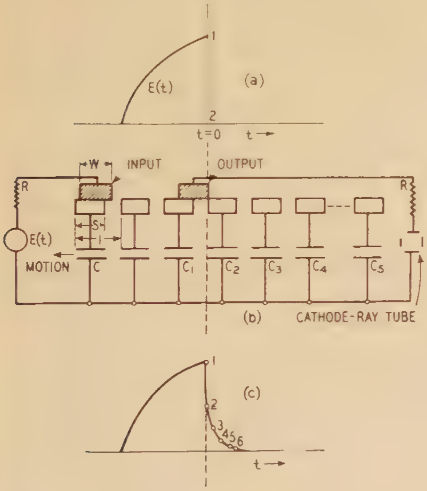

Figure 3. Distortion due to output brush making contact to more than one capacitor at a time

It is also advantageous to use a subtended brush angle of such a value that only one or two capacitors are in the brush circuit. The value of C, in equation 5, is the total capacity under the input brush.

It is not difficult to obtain good response as far as the RC value is concerned. The value of p, which determines the definition of the wave, is more important since the maximum frequency which can be transmitted by the network is determined by the number of capacitors required per cycle to make the frequency recognizable in the output circuit. These considerations determine the product pf. After the value of pf is chosen, the maximum value RC, which may be used as far as the input circuit is concerned, can be obtained from equation 5.

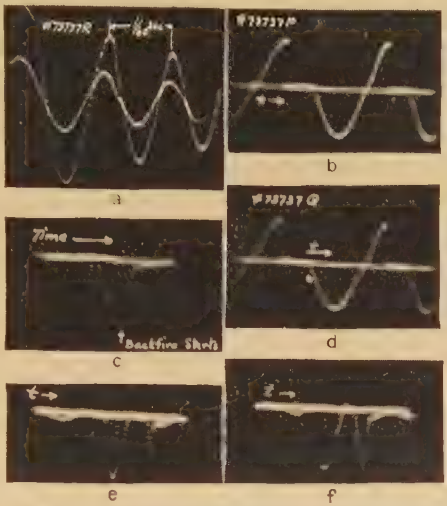

Figure 4. Oscillograms obtained with memnoscope

(*a*)—60-cycle transient

(*b*)—Wave as in figure 3*a* obtained without machine

(*d*)—Same wave as (*b*) with machine

(*c*), (*e*), (*f*)—Arc-back oscillograms of anode-to-cathode voltage of a mercury-arc rectifier

The Output End of Network

If contact is made at all times to not more than one capacitor, the output voltage wave into the receiving device will not be distorted provided p, the number of capacitors per cycle, is of sufficient number for the frequency transmitted.

If, however, the output brush makes contact with more than one capacitor at a time, then there will be a division of the charge and distortion will result. The effect of double contact can be seen from a consideration of a wave distribution as shown in figure 3*a*.

The action is as follows:

At $t = 0$ the voltage on capacitor C_1 (see figure 3*b*) is E_1. At the time contact is made to C_2, the voltage at the receiving device should be equal to zero according to point 2 on figure 3*a*. However, if the brush makes contact to C_1 at this time, as well as to C_2, C_2 will be charged to a voltage $E_2 = E^1/_2$. This transfer of charge by the brush continues and a distorted wave as shown in figure 3*c* will be obtained rather than the correct wave, figure 3*a*.

If a high-resistance brush material is used, the wave distortion will be reduced. Calculation shows that the resistance through the brush from bar to bar would have to be 1.25×10^6 ohms in order to make E_2 only one per cent of E_1 for the time t_1 used in this machine. A portion of this resistance would occur in the output circuit and distortion there would be enhanced.

Equation 7 in the appendix is for the wave from $t = 0$. This equation indicates that the maximum distortion occurs when contact is made to two bars at a time. For contact to more than two bars at a time, the distortion is reduced slowly; that is, as the log of a function of the number of bars spanned by the brush. Contact to only one bar at a time is best for minimum distortion.

The Short-Circuiting Brush

This brush circuit should have low resistance and inductance. Increasing the number of bars spanned by this brush does not affect the time constant unless the resistance is decreased in proportion. Brushes mounted axially with the commutator and separate and short leads from each brush to the common side of the circuit is possibly the best way to discharge capacitors.

Results With Memnoscope

Figure 4 shows the type of films obtained with the camera using a cathode-ray tube with a blue-trace screen.

Figure 4*a* shows a 60-cycle transient crossing the cathode-ray-tube screen two times. Each dot on the film represents the voltage of a capacitor.

Figures 4*b* and 4*d* are for waves of the type in figure 3*a*. These pictures were taken, respectively, without and with the memnoscope. They represent the anode-to-cathode voltage of an ignitron operating from a 60-cycle source of power.

Figures 4*c*, 4*e*, and 4*f* are oscillograms of random arc-backs of a rectifier. The films show anode-to-cathode voltage changing from normal inverse voltage to an arc-back. Films *c* and *f* show that the arc-back occurs near the crest of the wave, and *e* shows one starting at one-half crest voltage.

Value of Memnoscope in Research

The memnoscope has proved its value in rectifier research. The opinion has been that arc-banks in rectifiers occurred only during transition time. Oscillograms obtained with the memnoscope show that arc-backs do occur at other times during the inverse cycle. Oscillograms have given information which has led to improved designs and to very substantial increases in the ratings of ignitrons.

Appendix

To determine the frequency response at the input end, we may use the equation for voltage across a capacitor charged through a resistance r. If the input voltage is $E \cos(2\pi ft + \phi)$ the voltage at any time t is, if charge on $C = 0$ at $t = 0$

$$e_c = \frac{E}{2\pi fCZ}\left[\sin(2\pi ft + \phi) - \sin\phi\cdot\epsilon^{\frac{-t}{rc}}\right]$$

where

$$Z = \sqrt{r^2 + \left(\frac{1}{2\pi fc}\right)^2}$$

$$\phi = \psi - \tan^{-1}\frac{1}{2\pi frc} \qquad (1)$$

ψ = phase of E at $t = 0$

In this case the voltage impressed on the capacitor depends on the input voltage at the time contact is made. If the time duration of contact is t_1, when the brush leaves the capacitor being charged, the voltage on the capacitor will be

$$e_c = \frac{E}{2\pi fCZ}\left[\sin(2\pi ft_1 + \phi) - \sin\phi\cdot\epsilon^{\frac{-t_1}{rc}}\right] \qquad (2)$$

t_1, the time duration of contact in terms of the frequency f, and p, the number of capacitors per cycle is

$$t_1 = \frac{1}{pf} \qquad (3)$$

and

$$\frac{t_1}{rc} = \frac{1}{pfrc} \qquad (4)$$

Substituting in (2), e_c becomes

$$e_c = \frac{E}{\sqrt{1 + (2\pi frc)^2}} \times \left[\sin\left(\frac{2\pi}{p} + \phi\right) - \sin\phi\cdot\epsilon^{-\frac{1}{pfrc}}\right] \qquad (5)$$

This equation shows that a phase distortion and an amplitude distortion can occur. Since p must be made sufficiently large to give a recognizable wave, when the frequency desired is increased, the rc value must be decreased in order to make both the second term under the radical and the second term in the brackets negligible compared to other terms in the above equation.

The time of contact t_1, see figure 3b, in terms of commutator bar, brush, and insulation dimensions is

$$t_1 = \frac{w + s}{(rps)bl} \qquad (6)$$

Using this value for t_1 we can write (5) in terms of the dimensions, speed, and number of bars.

If contact is made at the output end to more than one capacitor at a time distortion will occur. If we consider an input wave as shown in figure 3a, and contact to two capacitors at a time, the output wave will be as shown in figure 3c.

This wave can be represented by equation (7), assuming $C_1 = C_2 = C_3$, etc., and a brush of negligible resistance

$$E_n = \frac{E_1}{2^{n-1}} = E_1\epsilon^{-(n-1)\log 2} \qquad (7)$$

where E_n is the voltage of the nth capacitor, and $n = 1$ for C_1, $n = 2$ for C_2, etc., and E_1 = constant. This gives an exponential curve for the output end, instead of a vertical line as desired.

Bibliography

1. **J. Slepian and L. R. Ludwig**, AIEE, October 1931, pages 793–6.

2. OSCILLOGRAPH WITH A MEMORY, **A. W. Hull**, National Academy of Science meeting at University of Virginia. Description and oscillogram given in *G. E. Review*, January 1936, page 72.

Discussion

H. P. Kuehni (General Electric Company, Schenectady, N. Y.): In the device described in this paper an electrical phenomenon to be recorded is first impressed on a set of rotating capacitors which are connected to commutator segments. Each capacitor is charged through the input commutator brush to a potential proportional to that of the electrical phenomenon at the time of brush contact. By means of a second commutator brush, which is advanced in the direction of rotation, the charged capacitors consecutively are connected to the oscillograph, thus recording in steps the event a definite time after its occurrence.

The accuracy of reproduction and frequency response of this device are largely functions of the number and size of the capacitors used, the speed of rotation, and the input and output circuit time constants, as well as the energy available from the circuit to be studied. For practical and economic reasons the number of capacitors, commutator segments, and speed of rotation obviously are quite limited. In the author's machine 147 0.01-microfarad capacitors were driven at a speed of 1,800 rpm. Under these conditions a 60-cycle wave is reproduced with 73.5 steps of 4.9 electrical degrees per step. However, a 600-cycle wave, for example, would be reproduced considerably distorted by only 7.35 steps with 49 electrical degrees per step. It is to be expected, therefore, that even though the circuit time constants can be made small to satisfy the response requirements, the limited practical number of capacitors and commutator segments render this type of recording device suitable for moderate frequencies only. It is questionable whether a device of this type can be built economically for high-frequency response as required, for example, in the recording of surges of short duration, switching transients, and the like.

For the recording of random phenomena Doctor A. W. Hull[1] made use of the afterglow of the fluorescent cathode-ray-tube screen. The recording photographic camera, being triggered through a thyratron by the disturbance itself, photographs the afterglow of the cathode-ray trace or the so-called tube screen "memory" of the event. The screen substance willemite, which is widely used in commercial cathode-ray tubes, has an afterglow of approximately $^1/_{20}$ second which is ample time for the camera to catch. An automatic three-tube cathode-ray oscillograph built on the screen "memory" principle has been in continuous and highly successful use for nearly two years in the General Electric Company for the study of random phenomena pertaining to power rectifiers and tube circuits. The cathode-tube screen afterglow can, of course, be used with any cathode-ray oscillograph providing the tube voltage is sufficiently high to produce a recordable trace of the transient. With the General Electric high-speed hot-cathode type-*HC*-15 cathode-ray oscillograph,[2] using a 15,000-volt permanently sealed glass cathode-ray tube, successful photographic memory records were obtained in experimental work of a transient as fast as a 1 × 5-microsecond impulse wave by triggering the camera with a relay energized from a charged capacitor through a thyratron fired by the impulse itself. The cathode-ray tube "memory" principle has practically unlimited frequency response and outside of a simple relay, capacitor thyratron circuit, and a camera, no extra equipment is needed. It is believed doubtful that the author's capacitor device can be made to have as wide a frequency range as the simple memory principle described by Doctor Hull.

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1. See author's reference 2.

2. ELECTRICAL ENGINEERING, June 1937, pages 721–7.

W. E. Pakala: Mr. Kuehni has questioned the economical use, at high frequencies, of the rotating capacitor network for memory oscillograms of random events, and mentions the use of high-persistence cathode-ray tubes for memory oscillograms.

The machine described was designed to give information as to conditions existing for two to four cycles prior to random arc-back in a mercury-arc or ignitron rectifier operating from a 60-cycle power source. For these conditions the capacitor machine has been very useful and entirely satisfactory.

In the cathode-ray-tube method of obtaining "memory" oscillograms of random events, it is necessary to keep the tube fully energized and the recurrent phenomena on the screen. This means that the recurrent or normal trace, while waiting for random

Remote Control of Network Protectors

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Synopsis: Two low-voltage a-c networks have been installed in Tennessee, using a radically different protective scheme. The customary master relays, phasing relays, and associated current transformers have been omitted from the network protectors using in their place a remote-control system of pilot wires operated from relays at the supply substation which protect the high-voltage cable feeders.

In contrast with previous pilot-wire-protected network systems utilizing looped primary circuits with secondary transformer fuses[1,2], these networks retain the radial supply and electrically operated secondary air circuit breakers of the more conventional systems.

Previous experience has pointed to operating advantages of a remote control system provided a thoroughly reliable installation could be secured at a reasonable cost. The system described does not exceed the cost of conventional relay installations and it is felt that inherent hazards to reliability have been overcome.

LOAD GROWTH in the business district of Nashville, Tenn., had made necessary the rehabilitation of the existing underground supply system consisting of overloaded 2.3-kv radial cables. Comparative cost estimates showed decided advantage of replacing the entire 2.3-kv system with its crowded ducts and aged cables with a low-voltage a-c network system supplied from four 13.2-kv cable feeders.

Successful operating experience with d-c pilot-wire systems for tie-line protection over a period of five years[3] led to the consideration of remote-control pilot wires for the proposed network system instead of master relays and phasing relays. Conditions particularly favorable to remote control were the fact that an entirely new network system was contemplated making the conversion of existing equipment unnecessary, the supply substation is located immediately adjacent to the network area, the fact that replacement of 2.3-kv cables with 13.2-kv cables would release ducts which would be idle except for remote-control cables, and that the arrangement of duct banks resulted in several "inside" ducts which would be of little use in power-carrying capacity.

Three of the four 13.2-kv cable feeders were connected in service on February 6, 1937, with the initial network step consisting of five units. At the close of 1937 a total of 34 units had been installed on the four cable feeders. Construction is proceeding in a steady program.

In Chattanooga a low-voltage network system is being installed to supplement a 2.3-kv radial underground system. By the end of 1937 a total of eight units had been installed on three 11-kv cable feeders. It is planned that the network will eventually replace all of the 2.3-kv radial underground system.

Operating Requirements

Network experience over a period of years has resulted in a rather imposing list of requirements for the network control relays, such as:

1. The network protector must trip for any short circuit or ground on the high-voltage cable feeder.
2. The network protector should trip on transformer magnetizing current or cable charging current with the supply breaker open.
3. The network protector should not trip due to small phase-angle differences in supply of various feeders.
4. The network protector must not trip during a fault on the secondary network.
5. The network protector must not trip during a fault on any other high-voltage feeder.
6. The network protector should not trip on power reversals at light loads or in case of regenerative loads.
7. The network protector should close when the transformer is energized with voltage of such magnitude and phase relation that power will flow from the transformer to the network.
8. The network protector must not close if resulting power flow would be such as to operate the sensitive tripping relay.
9. The network protector must not pump when the high-voltage cable feeder is energized through one network unit which has failed to open.

It is evident that limits usually imposed on the closing of a network protector are based on imperfect selectivity in its opening characteristics.

A tremendous amount of development work has been done by operating engineers and manufacturers in evolving relays or systems which could meet these requirements, and the remarkably good record of network relay performance[4] is a tribute to their work. One solution[5] has been to apply relays which are sensitive primarily to negative-phase-sequence quantities. Naturally such relays will not meet the requirements of opening on transformer magnetizing current, but operation approaching this can be achieved by providing a source of negative-sequence power at the substation. Another approach[6] has been to install power devices in the primary system for controlling phase-angle displacement of the various feeders supplying a common network. Doubt has been expressed regarding the universal application of either of these methods.

One engineer[7] has compared the operation of a network system to the conventional transmission network in which all switches are operated closed except for inspection or repairs or in event of system trouble, in which case only the circuit breakers which are necessary to isolate the fault are opened. Accordingly it has been suggested that requirements of network relays be reduced to (1) the network protector should close when its transformer is supplied with normal three-phase voltage in excess of the network voltage by a predetermined value (2) the

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The authors wish to acknowledge the assistance and co-operation of the underground distribution, design engineering, and field test personnel of The Tennessee Electric Power Company in the development and testing of this protective scheme, and the co-operation and encouragement of engineers of several utility companies. They also wish to acknowledge co-operation of the engineers of the General Electric Company in furnishing information on various other proposed methods of network protection.

1. For all numbered references, see list at end of paper.

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phenomena, will have some effect on the interpretation of films, since the repeated trace will photograph much better than the transients, which are single sweeps on the cathode-ray-tube screen. In other words, there is some "burning in" effect because of recurrent traces, whereas the intensity of the transient trace decays exponentially.

If a rotating capacitor delay machine is used with a cathode-ray tube, the intensity can be kept at a low level until the camera shutter is opened and high-speed cathode-ray screens can be used, giving pictures of only the trace desired. Another advantage is that a magnetic oscillograph can be used and oscillograms of several currents and voltages obtained simultaneously as economically as with, say, a battery of six cathode-ray tubes.

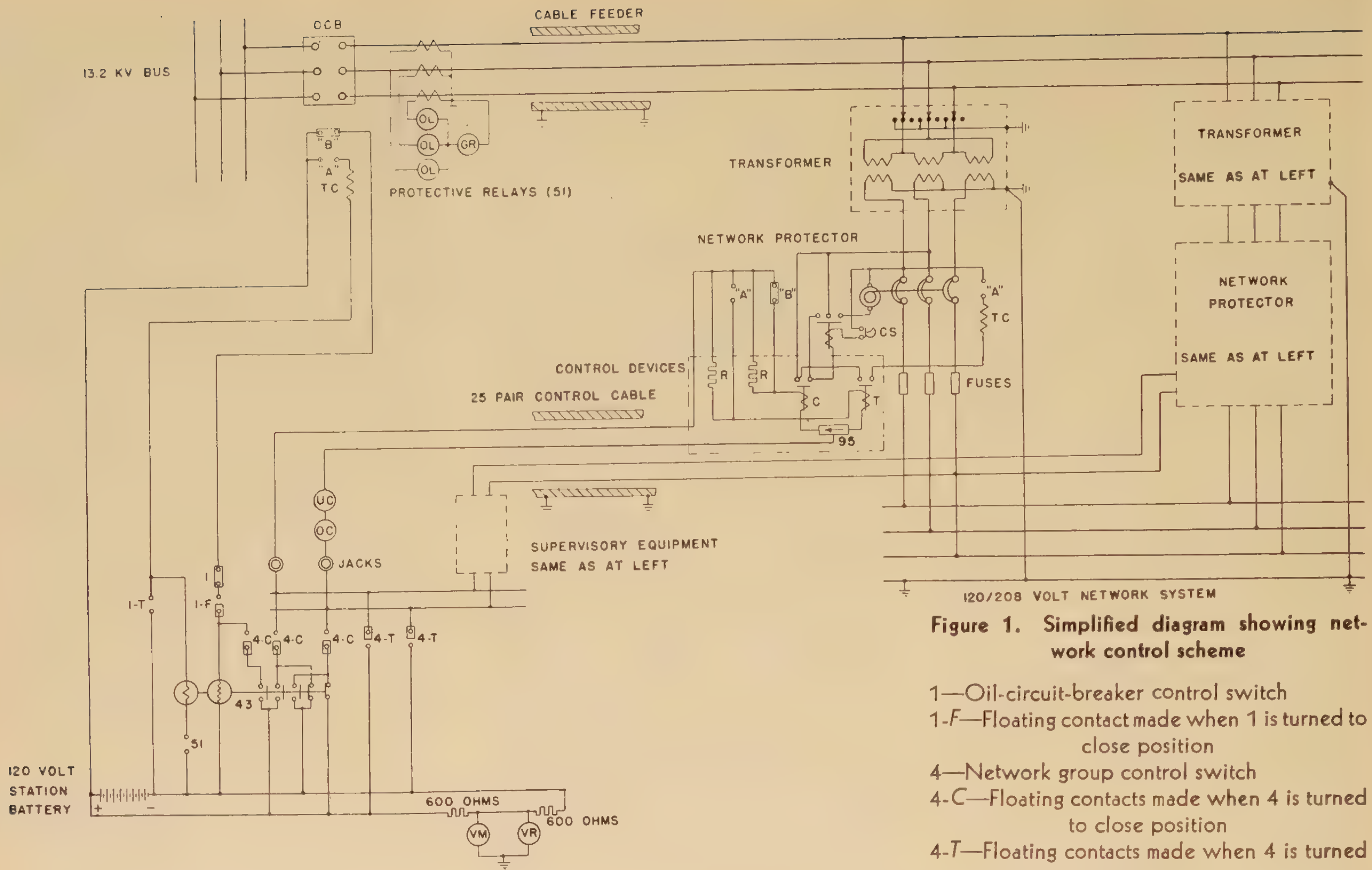

Figure 1. Simplified diagram showing network control scheme

1—Oil-circuit-breaker control switch
1-*F*—Floating contact made when 1 is turned to close position
4—Network group control switch
4-*C*—Floating contacts made when 4 is turned to close position
4-*T*—Floating contacts made when 4 is turned to trip position
43—Series-shunt reversing relay
51—Feeder protective relays
95—Copper-oxide rectifier with mid tap
C—Remote-control closing relay
T—Remote-control tripping relay
CS—Network protector motor cut-off switch
R—4,100-ohm resistor
OC—Overcurrent supervisory relay
UC—Undercurrent supervisory relay
TC—Trip coil
VM—High-resistance voltmeter
VR—Sensitive voltage relay

network protector should trip in case of a high-voltage fault or when opening means are applied at the supply substation.

A network primary feeder with its associated network transformers may be compared to a transformer in a power station which is operated in parallel with other units. Individual control switches provide separate manual control of the high-voltage and low-voltage breakers but internal faults trip both breakers.

This is the general type of control which has been provided for the remote-control network system, except that only two wires are used to connect each low-voltage air circuit breaker with the supply substation equipment resulting in depending on protective relays on a high-voltage feeder alone to determine short circuits in the protected zone.

Description of Control Scheme

Each feeder control panel at the supply substation is provided with two standard-size control switches, one to control the high-voltage oil circuit breaker for the cable feeder and the other to control the entire group of low-voltage network breakers associated with that feeder. Operation of overload or sensitive ground relays applied to the high-voltage cable feeder results in tripping the feeder oil circuit breaker and also tripping the entire low-voltage group, causing green lamps on both control switches to burn and sounding a station alarm which may be silenced by turning both control switches to the trip position. After trouble has been located and repaired the operator can energize the feeder and then close the network switches immediately or if desired he can energize the feeder and wait for a given test period before connecting the feeder to the network.

Among requirements sometimes listed for network master relays is that they shall provide a check on any possible incorrect phasing on the high-voltage or low-voltage side of a network protector during construction. This function is really a by-product of the opening and closing characteristics of the network relays and those who have had experience with incorrect factory wiring of distance relays and similar equipment would not like to trust such devices for a definite check on the adequacy of construction phasing. At the present time our construction forces prefer to check phasing electrically across a network protector with fuses removed but provision has been made for checking phasing of any new network unit or of any splice in a primary cable using equipment at the substation. Instead of using one potential transformer on each underground cable feeder, two such transformers are connected in open delta and a swinging panel with two 360-degree synchroscopes arranged with transfer switches so that a feeder cable may be energized from a new network unit or from a network unit beyond a new cable splice and exact phase relations checked at the substation.

Each primary radial feeder is protected by three inverse-type overload relays with instantaneous attachments and one inverse-type sensitive ground relay with instantaneous attachment (see figure 1). The contacts of all four protective relays are connected to the trip coil of the oil circuit breaker through a series coil of a battery reversing relay. This relay is also provided with a shunt coil which seals in from momentary operation of the series coil until it is released by turning the network group control switch to the trip position. The shunt coil is also operated from a "*b*" finger of the oil circuit breaker through a floating contact of the control switch, guarding against leaving the primary cable energized from the network (without normal protection) in case the feeder oil circuit breaker should open accidentally.

The reversing relay controls the group of network air circuit breakers on a feeder by reversing 125 volts d-c battery supply to the remote control pairs. Control battery is carried to each network protector on an individual pair of wires by means of number 22 gauge double paper-insulated lead-covered cable located in the same underground duct system with the primary supply cables. For the main runs one 25-pair cable is used with each high-voltage feeder and 10-pair cables are used for lateral runs to each network unit. One common pair for each feeder is terminated in a "condulet" type receptacle at every network protector for plugging in portable telephone equipment. Each control cable has four spare pairs terminated in each network protector.

Inside each network protector housing all relays, current transformers and associated wiring have been removed, leaving essentially an electrically operated air circuit breaker. Two small contactors are added operating in conjunction with one copper-oxide rectifier with mid tap and two fixed resistors to give closing or tripping impulses to the network air circuit breaker depending on polarity of direct current supplied at the substation. As a tripping or closing operation of the air circuit breaker is completed the auxiliary switch inserts a fixed resistance to reduce current in the pilot wire circuit from the operating value to the supervisory value. Figure 2 shows the contactors (*C* and *T*) mounted in the network protector housing. The rectifier and resistors are shown at the lower left. Interruption of d-c supply or the failure of remote-control pairs does not result in operation of the air circuit breakers but merely removes control from them.

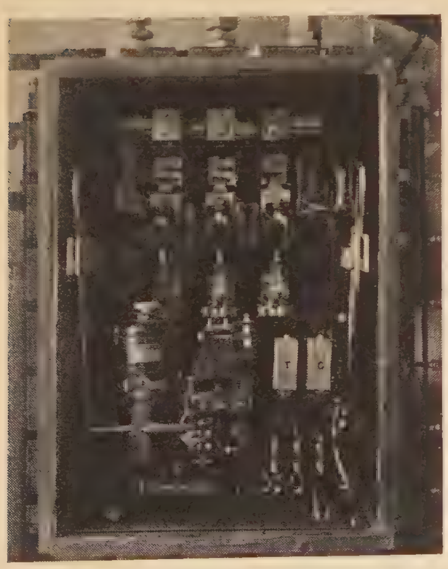

Figure 2. Mounting of remote control equipment in standard protector unit

Continuous audible and visible supervision of each pilot-wire circuit[3] is provided by means of a small overcurrent and undercurrent contactor for each pair located at the substation. Remote-control operating current is 130 milliamperes which is reduced immediately through air circuit breaker auxiliary switches to 25 milliamperes. The closing and tripping contactors at the network protectors operate on 75 milliamperes and drop out on 45 milliamperes, while at the substation the overcurrent contactors pick up at 75 milliamperes and drop out at 45 milliamperes and the undercurrent contactor picks up at 18 milliamperes and drops out at 11 milliamperes. A control alarm buzzer at the substation operates if current is above 75 milliamperes or below 11 milliamperes, or in case of a ground on any portion of the battery circuit. A row of telephone-type white supervisory lamps (see figure 3) is provided on the substation feeder switchboard panel with one lamp for each network protector. These lamps burn normally regardless of the position of the network protector but are extinguished if the overcurrent or undercurrent contactors indicate an abnormal condition. Although the alarm system is primarily for the purpose of supervising the remote-control circuits it also calls attention to the failure of an air circuit breaker to open or close (as directed by substation equipment), since the operating current is chosen to pick up the overcurrent contactor.

Under each supervisory lamp on the switchboard panel are located a set of telephone-type jacks for isolation and tests of the individual control pairs. One zero center d-c milliammeter is provided which can be used by means of a cord and plug to read current in any control pair. Thus the operator can determine readily whether an alarm indicates an open circuit, short circuit, or failure of the network air circuit breaker to operate.

An interesting by-product of individual control-circuit supervision is individual remote control of the network protector units. The same telephone jacks used for test and isolation of the control pairs can be used by means of a special plug to operate one or more network units to a position other than that indicated by the principal control switch. When the special plug is removed from the test jack the network protector returns to the position called for by the main control switch. Naturally the automatic battery reversing relay takes precedence over the individual jacks as well as over the main control switch, so that network protectors always trip in case of power trouble regardless of manual operation from the substation.

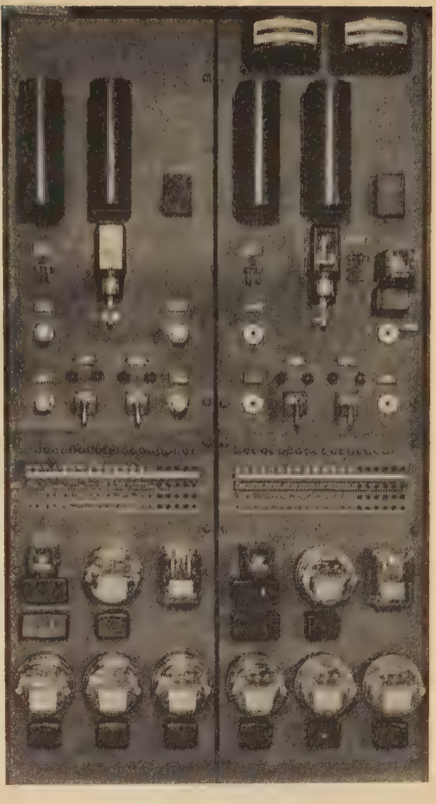

Figure 3. Switchboard arrangement of control equipment for Nashville network. Each panel controls one primary feeder and its network protectors

Figure 4 shows a front view of switchboard at the supply substation of the Chattanooga network. The control scheme is quite similar to the Nashville installation except that a row of keys has been provided for individual control of the network units using jacks merely for tests and isolation. A further difference is that the single white supervisory lamp for each network protector has been replaced by a supervisory red lamp and a green lamp, these lamps being operated from the same contacts on the overcurrent and undercurrent relays which are used in the Nashville scheme to operate the white supervisory lamps. The red and green lamps are connected at the substation end of the remote control pairs (between substation battery and the supervisory relays) so that a somewhat better indication of the position of the network protectors is given as long as the control circuit is intact and the protector operates correctly. Naturally complete indication

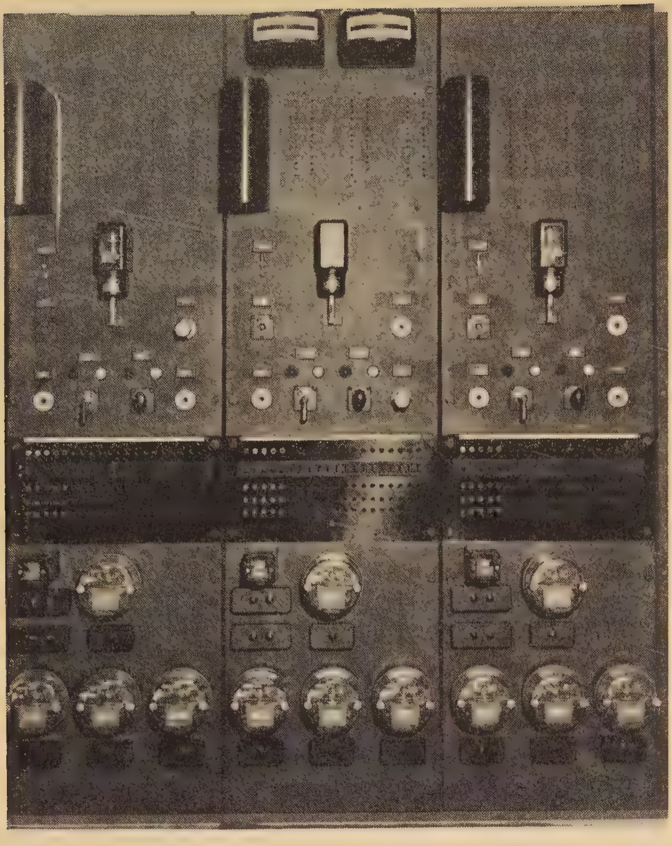

Figure 4. Switchboard arrangement of control equipment for Chattanooga network. Each panel controls one primary feeder and its network protectors

of the network switch position with the control circuit in trouble would require additional control wires. If the control pair is in trouble or if the network protector fails to move to the required position then the red and green lights at the substation burn dimly in series.

It may be noted that telephone type equipment has been mounted on the standard ebony asbestos switchboard by using a center section of thin bakelite arranged flush with the front of the $1^1/_2$-inches-thick composition panel.

Relative Cost of Remote Control Equipment

At the present time standard network protectors without relays or current transformers are being purchased from two leading manufacturers with a price reduction of about $400 per protector. Estimates based on the Nashville completed network with a total of 60 network protectors show that the pilot-wire cables and associated equipment can be installed for about 60 per cent of the price reduction on the 60 network units. These estimates include cost of the control cable and its complete installation with fireproofing but do not include any allocated cost for duct space. No credit is taken for the cost of telephone pairs. Cost of terminal equipment in the network protectors and at the substation is included. Many of the parts are quantity-production items used in communication and automatic control.

In cases where duct space for control-cable circuits is not readily available at moderate cost, consideration should be given to leasing a remote control pair for each network protector from the local communication company. Aside from the cost comparison, the advantage of relative freedom of exposure to power system troubles can be weighed against possible control-circuit outages arising from telephone protective equipment or maintenance procedure on the part of the communication company.

While variations in cable installation cost may be expected the resulting figures would still show positively that the remote-control system would not cost more than the conventional system. The fact that the selling price of the equipment omitted from the network protectors is nearly $600, whereas the present omission price is two-thirds as much points to probable additional economies in the future.

Reliability

It is generally conceded that the frequency of inspections of equipment which is likely to cause trouble has a pronounced bearing on the probability of failure of protective equipment to perform properly during system trouble. Attention has been called to this recently in connection with low-voltage a-c network operation.[4] Experience with transmission relays has emphasized the need of frequent inspections of protective devices and in the case of protective equipment which is difficult to inspect and which is exposed to hazards extending over several miles such as a pilot-wire circuit the use of continuous audible and visible supervision has been found highly effective. Although these conclusions were reached through operating experience and study, the curve of figure 5 has been prepared to illustrate the theoretical relation between the time required to locate and clear protective trouble and the probability of failure of the protective equipment to clear primary short circuits. The time of one hour at one end of the curve is taken as a typical value for remote-control equipment since within this length of time the operator can determine that an individual control pair is defective (grounded, short-circuited, or open-circuited) and can arrange to have this individual network unit removed from service even under peak load conditions such that it would be undesirable to remove an entire network feeder from service.

Experience of communication companies indicates that many troubles with underground lead-covered cables come about through the entrance of moisture into the cable through small defects in the lead sheaths. Several hours are usually required after the failure of one pair before the entire cable is involved. This was borne out in striking manner by the one case of control-cable trouble which has been experienced since the Nashville network system was started. A splice was known to be defective (due to special local causes) but construction was at such a stage that it was decided to leave the splice in service over a period of time and observe results. After the first pair caused operation of an overcurrent relay (indicating a high-resistance short circuit) a period of six days elapsed before another pair was involved. After an additional period of 12 days two other pairs were involved and at that time the defective splice was repaired. This trouble was due to the entrance of moisture through a defective splice into one of the 25-pair control cables.

Another case of trouble was discovered by means of the ground alarm. Isolation of various pairs at the substation by means of test jacks immediately located the faulty circuit which was then operated to trip the network protector and isolate it from battery supply. An investigation showed a vault half full of water and a defective network-protector housing had permitted moisture to collect on the control wiring resulting in the indication of a high-resistance ground.

The adequacy of supervision for preventing protective failures rests on troubles in the primary equipment and control equipment being reasonably independent of one another, and precautions have been taken to insure this condition. Special short-circuit tests were made to determine the possible difference of ground potential between the supply substation and network units from which calculations indicate a maximum difference of 200 volts under the most unfavorable short-circuit conditions.

One chief cause of concern has been the likelihood of primary cable burning control pairs in two or destroying a network control cable. The choice of control scheme has reduced the possible damage from such a contingency. In case of a primary cable burning its associated control cable, correct operation is secured if the tripping impulse is given to the network protectors before any control cable pairs are damaged. The use of instantaneous devices on the protective relays and high-speed control equipment insures that the trip plungers at the air circuit breakers will be in motion less than four cycles after the beginning of the fault. Since interruption of d-c supply does not cause the network protectors to open, the damaging by a power cable of a control cable associated with another feeder does not impair operation as long as the control cable can be repaired and restored to service before the occurrence of a second high-voltage fault.

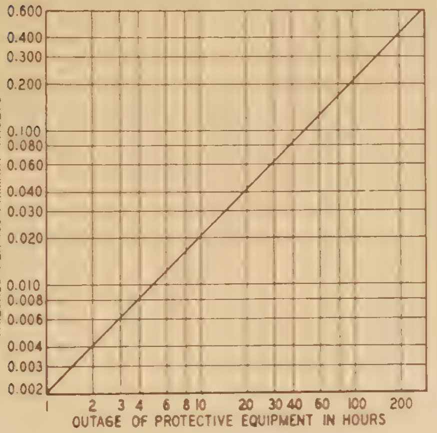

Figure 5. Curve showing probable failures per 100 primary feeder faults of network protector units to trip due to control pair and control equipment failures extending over various periods of time

In order to minimize the possibility of any damage to control cables from power equipment the control cables have been fireproofed at every vault in the same manner as the power cables and wherever feasible they are located not too close to the power cables or splices. As a check on the adequacy of such fireproofing, short-circuit tests were arranged at system voltage, using short sections of three conductor power cable and splices of such cable placed within five inches (surface to surface) on racks from a section of fireproofed control cable. An internal fault from one conductor to sheath was made before the test in each sample of cable and oscillograph elements arranged to record any change in normal direct current in any pairs of the control cable and also to record through a current transformer the passage of any current to the sheath of the control cable.

A series of 15 short-circuit tests were made energizing the faulted cable specimen with a three-phase grounded-neutral 11-kv power source of sufficient capacity to provide a ground current of 7,000 amperes. The duration of these short circuits was varied from 5 cycles to 30 cycles and in no case was there any disturbance to the control current and in none of the tests did the arc cause any current to flow in the control-cable sheath. Figure 6 illustrates the arrangement of test cables and shows burning of adjacent surfaces after a short-circuit test.

The extremely remote possibility of an entire control cable being out of service during a primary fault was examined by calculating the division of fault current through the entire network with a short on a primary feeder. Studies showed that all protector fuses on the faulted feeder would blow without damage to equipment. This situation should apply to any network designed for adequate burn-off characteristics.

Many failures of network protectors to clear primary faults are due to troubles in the network protector mechanisms. Since more than one-half of all network operations are classed as "miscellaneous" or unintentional[4] a control system which eliminates practically all of such operations should result in improving the performance records of network protector mechanisms for the same frequency of maintenance.

Maintenance

All devices have been applied with ample margin, especially those located inside the network protector housings. For example, the continuous current through the copper-oxide rectifier is less than 25 per cent of the rated current of this unit. The normal rectifier resistance is under 10 per cent of the total series circuit permitting wide variations with temperature without seriously affecting the value of operating current. Although it is not required for reliable action, the pilot wire operating current may be held within 10 per cent of its rated value by means of tapped resistors located in the substation even if aging of a rectifier unit should raise its forward resistance to as much as five times the normal value. It is evident that there are no fine adjustments to be made to the protective equipment even on the more accessible apparatus located at the substation. Protective maintenance then becomes primarily a matter of repairing any failures in the control cable.

A control system which eliminates practically all unintentional protector operations should reduce trouble and expense of maintenance on the network protector mechanisms. It has been noted on power systems that an oil circuit breaker which is approaching a stage of uncertain operation due to sticking, weak springs, wearing of latches and rollers, or similar causes will frequently give forewarning of such a condition by operating sluggishly on the tripping operation if it has been standing closed for sometime (although subsequent operations for tests may be at normal speed), or by failing to

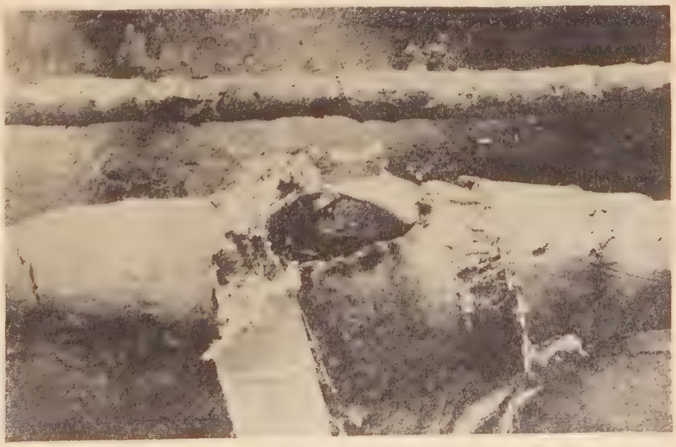

Figure 6. Tests illustrating integrity of remote control when exposed to a 7,000-ampere short circuit on adjacent power cable

latch on the first attempt to close it. It seems entirely probable that a system which calls audible and visible attention of the operator to any initial failure to latch or to any sluggishness in opening of a particular network protector will aid in a program of maintenance which should forestall many mechanical failures.

In contrast with a remote-control system the conventional network-protector relays must be adjusted very closely and slight variations in their characteristic due to temperature, corrosion, and loose connections, are quite serious. Many have found the maintenance and tests of network relays to be extremely difficult when performed at the network protector location[8] and two leading manufacturers now supply readily detachable relays so that these may be checked in the laboratory and then installed in the network protectors.

Additional Operating Features

Design of protective equipment has been concentrated on securing a thoroughly reliable installation at reasonable cost and it is planned that no other features will be added until after considerable experience and study of the present installations. However consideration may be given in the future to the installation of temperature and pressure relays in each network transformer using existing remote-control pairs. One possibility would be to permit the temperature and pressure contacts to send an alarm or tripping impulse over a common pair for all the units on one feeder cable with auxiliary contacts to trip the protector at the transformer involved and open its d-c control circuit thus providing instantaneous indications at the substation of the number and location of transformers involved without the use of coding. Consideration has sometimes been given to differential protection of network transformers but there has been no means of tripping the high-voltage feeder in case of low-voltage transformer trouble. One common pair for each feeder could be used for such a purpose, using the individual control pair for indicating the location of the transformer which had caused the feeder to trip.

Individual control of the network units can be used to considerable advantage without installing additional equipment. Consideration is being given to the installation at the substation of three sensitive single-phase wattmeters of low current range which may be connected to the current transformers on any feeder by means of transfer switches. Auxiliary current transformers would be connected wye-delta and used to bring wattmeter current in phase with current at the network-protector terminals. After a secondary fault or on any routine basis the operator can open a group of network protectors associated with the feeder and then close one of them with individual control jacks. The wattmeters may then be switched to the feeder supplying the one network unit and wattmeter readings would instantly show if there were any fuses which had blown during secondary trouble or due to mechanical defects.[9] Readings could be taken one at a time on all the network units on one feeder in a few minutes. Such a procedure would also indicate possible overloads on any transformer unit. This scheme has been tried using a special portable wattmeter and indications of a blown fuse are quite positive. Readings obtained from this method from the substation on individual units check very closely with current readings taken at the vaults.

Conclusions

1. The remote-control system described can be applied to the protection of many network systems at reasonable cost and in some cases at a substantial saving in cost over systems with conventional relays.

2. The remote-control system offers distinctive advantages in simplicity, flexibility, freedom from pumping, decreased maintenance trouble and expense on relays and protector mechanisms and suitability for a wide range of supply systems.

3. Operating experience must provide the final proof of the adequacy of any protective system, and the relatively low rate of primary failure on an underground network may require that such operating experience continue over a period of several years for conclusive results. Nevertheless it is felt that careful consideration has been given to all features and that operating and short-circuit tests have been carried far enough to predict excellent operation. Previous experience with pilot-wire circuits and their supervision points toward a protective design of high reliability.

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Discussion

L. H. Hill (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): Messrs. Brownlee and Dent have developed a low-voltage a-c network system devoid of all sensitive and unnecessary relays, without sacrificing the flexibility of the more complicated automatic non-pilot-wire control systems. In addition it provides the means for controlling the operation of any one of the switches between the transformer and the low-voltage mains.

Continuous supervision of the pilot circuits, and their subdivision into small parts, without complication, should prove entirely satisfactory. It is a scheme that may be applied to systems of any primary voltage without introducing the complications that would follow with other known pilot-wire systems.

The Brownlee-Dent system should find wide application in the smaller areas where the cost of duct space is nominal or of course also in larger areas if pilot wires can be economically installed.

J. B. Hodtum (Allis-Chalmers Manufacturing Company, Pittsburgh, Pa.): From a description of the authors' pilot-wire-controlled system, it appears that they have greatly simplified the operation of low-voltage a-c network systems. The third conclusion of their paper will really prove the merits of this system.

There is some background of course for the use of pilot-wire-controlled circuits as they have had wide use in Europe, especially in England. It seems that the authors have taken every possible precaution to supervise continuously and to guard against failure of any part of the control system involving the entire feeder. As pointed out, the control system may be extended to include, for example, differential protection of individual transformers which may even be made automatically to disconnect a feeder. It is questionable, however, whether automatic tripping of a feeder due to trouble, in a single unit, is advisable.

It appears that this system may be an advance in the art in that it permits individual transformers to carry loads in the reverse direction, since such operation would really mean that energy is being transferred from one part of the low-voltage system to another part over the high-voltage feeders instead of through the low-voltage network itself.

E. E. George (Tennessee Electric Power Company, Chattanooga): The authors have touched lightly on several important features of this new remote-control system. One feature is the possible use of control cables leased from a communication company. In Chattanooga and Nashville it was found that the telephone company could reach each transformer vault with a control pair over an underground route separate from the power route. This installation would usually be through the building adjacent to the transformer vault. However, the availability of a large amount of excess duct space made power-company-owned control cables somewhat cheaper.

If the communication company could establish a group rate for several pairs in the same area or in the same cable, avoiding long central-office loops there ought to be a considerable field of future business in certain cities that might use this new network control.

A feature that has appealed strongly to the operating, maintenance, and construction departments has been the availability of telephone service in each transformer vault. The portable telephones used by the underground crews and test engineers are furnished by the telephone company and permit ready communication between vaults and with the distribution dispatcher, assistant dispatchers, maintenance supervisors, and all other points.

This new system with its manual group or individual control of protector opening and closing by the operator at the supply station may be attractive to the metropolitan companies requiring sectionalizing in case of shutdown. We would like to have comments from those more familiar with this problem. Although about everything possible has been done to test out the new system, the real test will be the emergencies that may occur in the future without engineering, test, dispatching, and maintenance departments right on the scene. Such emergencies occur rarely, and it is hoped that other companies will make installations of this type of remote control so as to expedite the development work and to provide service for the benefit of the industry in general.

L. F. Kennedy (General Electric Company, Philadelphia, Pa.): The authors have made the statement that the limits placed on the closing characteristic of the network relay are due to the imperfect selectivity of its tripping characteristic. I should rather say that all the limits under which the network relay must operate, either to trip or reclose, are brought about by combining in one device both protective and control functions. It naturally follows that the device which meets these requirements needs more maintenance to insure reliable operation. The authors' familiarity with other protective relays will bear out the statement that as the operating requirements become more severe, the maintenance is increased.

The authors have installed the pilot-wire system at a saving in cost over the conventional network protector. At the same time they indicate savings in maintenance through the use of their system. But this has been done by setting up a new set of requirements, or rather the waiving of some of those normally met by low-voltage network protectors, and it would seem proper that any economic comparison then should be made between a network protector and a pilot system fulfilling the same requirements.

Relay equipment to trip on feeder faults only would be relatively simple, and if reclosing were permitted whenever the feeder voltage is approximately normal (corresponding to primary network practice), the over-all relay picture would be considerably changed. With such equipment relay and protector maintenance could be reduced and, since the protectors would operate only under short-circuit conditions, longer life would be obtained.

The pilot system operates basically in the same manner as the protector but in addition provides continual indication of each protector position and permits manual operation of the protectors either singly or by groups. The value of indication and control, even if considered to be small, is an item favorable to the pilot system.

It would seem necessary, therefore, to draw up a new set of operating requirements wherein the desired relay characteristics are definitely shown and then compare installed cost and maintenance of the two systems. If on such a comparison the pilot system is shown to be less expensive, it can unquestionably be justified. If the pilot system is more costly, it may still be justified by evaluating the indicating and control features.

I have purposely omitted any consideration of relative reliability in the foregoing comments. With simpler relay equipment I should be inclined to consider it more reliable than the pilot, but this is admittedly largely my own personal opinion. Certainly experience of the past few years has demonstrated that a pilot system of this type will show a high degree of successful performance. Given an equal amount of experience with both systems, perhaps the reliability should be considered equal.

To me the successful operation of the authors' system opens up the whole question of operating requirements of low-voltage networks. It is perhaps possible that these requirements have been made too severe and that we may see in the near future a general lessening of them accompanied by a reduction in maintenance expense on the whole system.

F. Von Voigtlander (The Commonwealth and Southern Corporation, Jackson, Mich.): The system of remote control of network protectors described in this paper appears to be a considerable advance in control systems of this type, and at the same time it achieves that goal sought by all of us, that of obtaining something better at a lesser cost compared to conventional methods.

The installation cited for a basis of comparative costs, involves a total of 60 network-protector units. There is, no doubt, a minimum system to which it would be economical to apply a network control scheme of this type. I would like to ask the authors' opinion of the approximate size of such a minimum system.

T. G. LeClair (Commonwealth Edison Company, Chicago, Ill.): A pilot-wire scheme for the control of network protectors is naturally of more interest to a Chicago engineer than any other because the Commonwealth Edison Company has made wider use of pilot-wire relay protection than perhaps any other metropolitan utility. Also, the operating record of the pilot-wire relaying system has been much better than that of other relaying systems. For many companies the cost of the pilot-wire control scheme for networks would be materially increased because of the duct cost which must be added to the cable cost. However, for larger cities a majority of the pilot cable would be installed in large duct sections where the central ducts cannot be used for power cables due to temperature limitations, but are available for pilot or control cable. Therefore, a large part of the duct cost charged to the pilot cable would be more theoretical than real.

The pilot-wire system suggested by Messrs. Brownlee and Dent might even be extended to include greater protection than at present by the addition of differential relays on the network transformers and a tripping circuit which would trip the primary and all the secondary breakers automatically for a fault on the transformer secondary in the zone now unprotected.

One missing feature of the scheme suggested in the paper is the inability to trip on back-feed through the network units without the use of the control equipment at the supply end. This is probably only of importance for a system fed from two independent sources where it is desirable automatically to transfer the entire network load to one source in the event of a major catastrophe which would make the feeder circuit breakers inoperative due to fire or explosion in the other source.

An item of maintenance expense which might be important in metropolitan systems is the relatively large number of cable cutovers which would be necessary on the pilot cable as the network system grows and transformers are frequently transferred from one feeder to another, either singly or in groups.

Chase Hutchinson (Tennessee Public Service Company, Knoxville): This type of system should appeal to many operating men since it offers a means of securing almost any desired information on vault conditions and at a low cost. Load, temperature, pressure, and other indications of condition can be transmitted, either to inform the operator, trip the vault protector, or trip the entire circuit. It eliminates much of the loss of time in checking protector positions and almost immediately locates a protector which sticks in the closed position.

Balancing some of these attractive advantages are some disadvantages the writer believes deserve careful consideration:

1. What is going to happen if a street cave-in or duct-line failure occurs? Can the network system

be depended upon successfully to blow simultaneously the required number of protector fuses?

2. In most cases the question of duct cost for the pilot cable cannot be neglected.

3. Since the pilot wire cost varies with the length of the feeder, and the network relay cost varies with the number of transformers, it appears the "beginning" cost of the pilot wire system might be higher than the conventional protector.

4. In attempting to peer into the future capital cost of these systems, one is inclined to argue thus: The pilot wire system is largely made up of "production items," and to a considerable extent is assembled in the various transformer vaults and manholes. The cost of this type of work is apt to increase in future years. On the other hand, the conventional protector has had to stand an enormous development and advertising cost. The present version is reliable, and with general acceptance of the system at hand it seems reasonable to believe the cost of protectors will decrease in the future years.

5. The spot network using pilot-wire protectors may be prohibitively expensive.

It appears to the writer that the system devised by Brownlee and Dent is comparable to the conventional network protector system equipped with supervisory control, consequently, where supervision of the protector and vaults is considered necessary, the scheme appears to offer a lower cost method.

J. H. Neher (Philadelphia Electric Company, Philadelphia, Pa.): The use of low-voltage a-c networks is in general limited to relatively large urban load centers, and as a result not many relay engineers have need to study this phase of the relay art. Despite this fact, however, all relay engineers can well profit by a careful study of this paper. The straightforward manner in which the authors, unencumbered by previous notions as to how network feeders could be relayed, have produced a new system, designed from the ground up to do the specific work at hand, should be a good guide in the design of other types of relay systems.

The authors' tests demonstrating the independence of the control circuits with respect to short circuits in the power circuits, are most interesting. The results of these tests, together with the relatively low cost of installation of the control cables, open up a large field for the use of power company owned-and-installed communication circuits for relay protection and remote control.

W. R. Brownlee and **W. E. Dent, Jr.**: The beginning cost of a remote-control network system will naturally be greater per network transformer than the complete installation as pointed out by Mr. Hutchinson. The answer to this question and also to Mr. Von Voigtlander's question concerning the minimum size network system to which remote control could be applied economically is best given by considering specifically the present status of the Chattanooga network. The control equipment cost per network transformer is determined partly by the fixed terminal cost at the substation, but more by the length of control cables as determined by the distance from the supply station to the beginning load center. In the case of the Chattanooga network the supply substation for the present three-cable system is 0.8 mile from the load center of a small area, resulting in a control equipment cost of almost exactly the value of the price reduction of the network protectors. The demand of the present Chattanooga network is 1,500 kw which could be considered as the minimum system (based on cost alone) with the supply point approximately one mile from the load center.

As pointed out by Mr. LeClair and Mr. Hodtum the remote-control system lends itself to the ready application of differential protection of network transformers. In conventional systems the protectors or backup fuses will usually separate the network from a short circuit on the secondary of a transformer but proper co-ordination of the high-voltage feeder relays prevents automatic disconnection of the primary feeder in case of transformer secondary trouble. Probably protection of this zone has been omitted due both to the inherent difficulty of such protection and to the infrequency of transformer faults involving the secondary only.

The authors do not agree altogether with Mr. Hodtum that differential protection of network transformers should merely sound an alarm at the substation. Present remote indicating equipment transmitting indications of over-temperature or over-pressure of a network transformer do not usually trip feeder breakers, since their indication is not altogether positive and since it may indicate merely a secondary fault between turns which would gradually build up pressure over a period of minutes or even hours. Since most of these present systems are looped through all transformer vaults and depend on coded signals for determination of the transformer in trouble they are not suitable for instantaneous disconnection of a feeder if such were desired. It is the authors' opinion that any fault in a transformer sufficient to operate a differential relay requires immediate action and should be disconnected within a few cycles. Probably the general application of differential protection will be governed by the frequency and seriousness of faults beginning on transformer secondaries and also by the effectiveness of temperature and pressure devices, many of which have been installed in the last three or four years.

Mr. LeClair raises a pertinent question in cases where a network is supplied from two or more busses in the same or different substations. Naturally a major failure of a feeder oil circuit breaker could prevent this breaker from clearing a short circuit or even from opening mechanically. Usually differential or backup-type bus protection will be employed to disconnect all sources of power from the bus and extra contacts of the bus protection auxiliary tripping relay should be connected to the shunt coil of the reversing relay (device 43 of figure 1) of each feeder, thereby preventing the network from feeding the short circuit regardless of the condition or position of the feeder breaker.

Mr. Hutchinson's question regarding duct-line failures apparently considers a serious and infrequent disturbance of such a nature as to destroy first one or more control cables and second the power cables associated with those particular control cables. The calculations mentioned in the paper in connection with this extremely remote possibility considered a fault on one of the three or four primary cables with its protection completely removed and it was found that the backup fuses would operate without damage to equipment. These network systems have not been designed to operate with two cables out of service on a three-cable or four-cable system and consequently no studies have been made of simultaneous faults on two or more primary cables with protection previously removed.

Mr. LeClair's question regarding maintenance expense of transferring control cables when network transformers are transferred from one feeder to another is rather difficult to answer. Obviously a reconnection of cables at the network units would involve appreciable maintenance expense. One possibility would be to leave the secondary cables connected at the network transformer end and merely exchange pairs between adjacent control panels at the substation end. Proper coding of the control cables would permit ready identification of pairs from a key drawing showing the routing of each separate control pair. The result of having three or four pairs of one feeder located in the 25-pair control cable for another feeder is not as serious as it might seem. The resistance of terminal equipment at the substation in series with each control pair is enough to limit short-circuit current in a control cable to a few tenths of an ampere. The voltage on the pairs is maintained at approximately 65 volts to ground through a resistance of some 40,000 ohms (see figure 1). Furthermore the accidental short-circuiting, open-circuiting, or grounding of a control pair does not result in improper operation of any network protector and accordingly all construction splicing and maintenance of control cables can be made if desired without removing battery supply from the cables.

The authors cannot agree with Mr. Kennedy that any network operating requirements have been waived, but are convinced that the long list of requirements of conventional relays are solely for the purpose of fulfilling properly the simple operating requirements outlined in the paper. Even if operators were willing to waive the disconnecting function of network protection, and send a man to each vault whenever a clearance is required, it is doubtful if much simpler equipment can be readily designed to trip on feeder faults only. That is, conventional relays set insensitive enough to prevent improper operation on various power reversals might not be sensitive enough to operate in case of a ground on a primary cable using customary delta-wye network transformers and shielded primary cable. The authors are pleased to have a manufacturer who sells large numbers of network protectors confirm their opinion that protector maintenance will be reduced and operation improved if all "miscellaneous" or unnecessary operations are eliminated.

Positive-Grid Characteristics of Triodes

By RICHARD W. PORTER
ASSOCIATE AIEE

Synopsis: The total emission current in a vacuum tube can be expressed by the familiar space-charge equation. This paper shows theoretically that the ratio of plate current to total current should be a function only of the ratio of grid to plate voltage, and introduces experimental data to show that the function can be represented by a single exponential term. The exponential function is combined with the space-charge equation to obtain an empirical equation for the positive-grid plate-current characteristic. A simple, experimental method of obtaining the constants in this equation is described.

THE NEED for higher efficiency in radio-frequency power amplifiers makes it desirable to operate vacuum tubes with grids strongly positive for a short interval in each cycle. When the grid of a tube becomes positive, not all the electrons which leave the cathode will go to the plate; some of them will be collected by the grid. Therefore, the plate-current equation[1] which has been used for negative and low positive grid potentials assuming negligible grid current, will not apply. This paper presents a modification of the usual equation which takes account of the division of current between grid and plate. The object is to obtain a simple expression which will give approximately correct values of plate current when the grid is strongly positive, rather than to attempt to analyze in detail the various phenomena which occur within the tube.

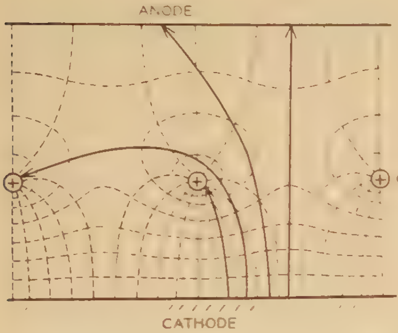

Figure 1. Possible electron paths in tube with positive grid

Total Space Current

It has generally been assumed that the basic space-charge equation

$$i = k(e_p + \mu e_g)^n$$

holds equally well for both positive and negative grid potentials, provided the current i includes all the electrons which leave the cathode, both those that go to make up the grid current and those that go to the plate. This assumption follows from the usual derivations based on the work of Langmuir[2] and Van der Bijl,[3] provided there be sufficient emission from the cathode to maintain the space charge, and that there be no unusual interaction between electrons after they leave the cathode space-charge region. Its validity is strikingly illustrated by the constancy of the total current in the following data for the Radiotron *UV* 207 in which grid and plate voltages were varied holding constant the sum of the plate voltage plus the grid voltage times the amplification factor.

The equation for the total space current can therefore be written

$$i_p + i_g = k(e_p + \mu e_g)^n \qquad (1)$$

where k, μ, and n are constant and have the same values when the grid is positive as when it is negative.

Division of Current Between Grid and Plate

In considering the problem of current division between the grid and the plate, first examine the path of a single electron which is emitted from some point on the cathode with negligible velocity. It will move as shown in figure 1 through a complicated electric field pattern, perhaps reaching the grid, perhaps the plate. If the grid and plate voltages are increased but kept in the same ratio, the magnitude of the field at any point will increase, but the field pattern will remain the same. Under these conditions, it seems reasonable that the electron paths also should remain the same, although the velocities may increase. This fact is proved mathematically in appendix *A*. The destination of any particular electron, therefore, will depend only on the ratio of the grid voltage to the plate voltage.

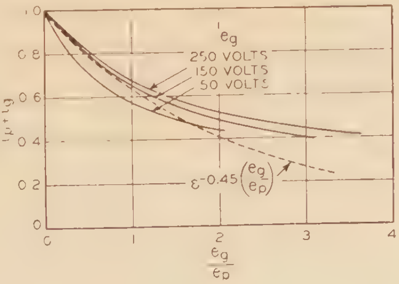

Figure 2. Current division in type-46 tube with grids connected together

Generalizing from the single electron to many electrons, there follows the important conclusion that the division of current between grid and plate should be a function only of the ratio of grid to plate voltage, and for any given ratio should be independent of the magnitudes of these voltages. The assumptions implied in this generalization are, (1) no emission of electrons by grid or plate, (2) no interaction between electrons after they leave the cathode space-charge region, (3) negligible initial velocity, (4) no interaction between the electrons and gaseous molecules. The nature of the functional relationship must be such that the ratio of plate current to total current will be unity when the grid voltage is zero, and will approach but never become zero as the ratio of grid to plate voltage becomes large.

Experimental Data

Data taken by the writer for the type-46 tube at high positive grid voltages tend

Table I

e_p	e_g	$e_p + \mu e_g$	i_p	$i_p + i_g$
500 v.	500 v.	10,500 v.	2.3 a.	3.35 a
2,500	400	10,500	3.1	3.20
4,500	300	10,500	3.25	3.25
6,500	200	10,500	3.30	3.30

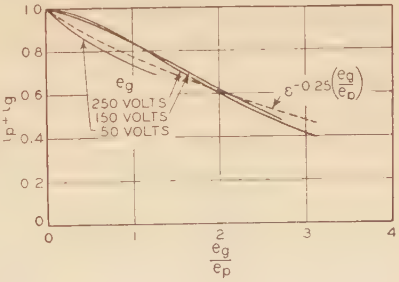

Figure 3. Current division in type-46 tube with grid 2 connected to plate

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RICHARD W. PORTER is employed in the engineering general department of the General Electric Company, Schenectady, N. Y. This paper is part of a dissertation presented for the degree of doctor of philosophy at Yale University.

1. For all numbered references, see list at end of paper.

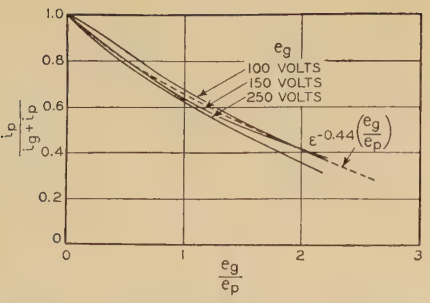

Figure 4. Current division in Westinghouse EX 50 50-watt triode

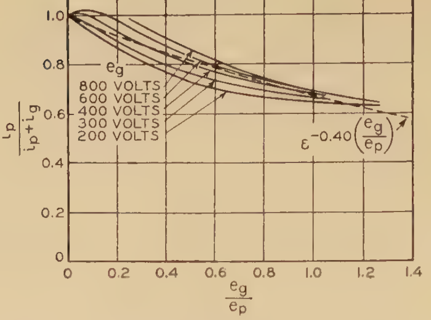

Figure 5. Current division in Radiotron UV 207, SKW triode

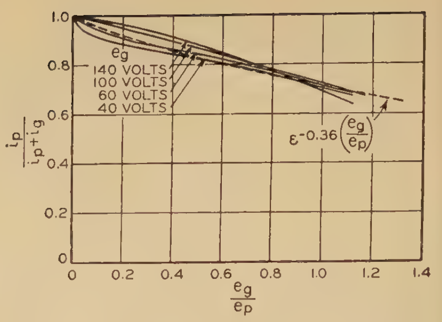

Figure 6. Current division in General Electric FP 169, 150-watt triode

to confirm these predictions and at the same time to justify the assumptions on which they were based. See figures 2 and 3, in which the ratio of currents is shown as a function of the ratio of voltages for various values of grid voltage. Except for the secondary effects which were assumed negligible, all the curves for each tube should be exactly the same. Similar curves have been plotted from data taken by Kozanowski and Mouromtseff[5] for the Westinghouse *EX* 50 tube and from published data on various RCA and General Electric tubes. Of these latter the *UV* 207 shows the highest discrepancy and the *FP* 169 the least. It is significant that the *UV* 207 characteristics show large secondary emission currents from the grid, particularly in the region of largest discrepancy, whereas secondary emission is not prominent in the *FP* 169. Data for the *EX* 50, the *UV* 207, and the *FP* 169 are shown in figures 4, 5, and 6.

These comparisons lead to the conclusion, perhaps already foreseen, that secondary emission is the principal reason for the failure of the current ratio to be a simple function of the voltage ratio. However, the greatest divergence observed was only about 17 per cent, or nine per cent variation from the mean. For the region near $E_g = E_p$, the greatest variation to be found in the published data is less than four per cent from the mean. Errors in measurement and drafting are sometimes as great as this.

The exact nature of the relationship between the current ratio and the voltage ratio depends on the construction of the tube and is too complicated a matter to treat here. However, its general form is that of an exponential. It will be assumed therefore that all tubes can be represented by

$$\frac{i_p}{i_p + i_g} = \epsilon^{-\alpha\, e_g/e_p} \qquad (2)$$

where α is a constant used to fit the equation to the data. For practical purposes it is usually well to choose α so the curve will match the data at $e_g = e_p$, for it is in this region that a tube delivers most of its useful power as a high-efficiency radio-frequency power amplifier. Representative exponentials are shown in dashed lines in figures 2 to 6. The error in this assumption is seen to be approximately the same as that introduced by assuming the existence of a simple functional relationship between ratios.

Plate Current

Combining the expression for total space current (1) with that for the fraction which goes to the plate (2), we obtain an equation for the plate current alone

$$i_p = k(e_p + \mu e_g)^n \epsilon^{-\alpha\, e_g/e_p} \qquad (3)$$

This equation as it stands is correct only when e_g and e_p are both positive. When the grid is negative the exponential term remains equal to one and when the plate is negative, it is zero.

It is not necessary to have complete oscillographic data on a tube in order to evaluate the constants of equation (3). They can be determined by a few simple measurements of plate and grid current at low voltage. For the composite diode characteristic $e_g = e_p$ equations (1) and (3) become

$$i_p = k(1 + \mu)^n e_g{}^n \epsilon^{-\alpha} \qquad (4)$$

$$i_p + i_g = k(1 + \mu)^n e_g{}^n \qquad (5)$$

Taking the logarithm of both sides,

$$\log i_p = \log \{k(1 + \mu)^n\} + n \log e_g - \alpha \qquad (6)$$

$$\log (i_p + i_g) = \log \{k(1 + \mu)^n\} + n \log e_g \qquad (7)$$

Equations (4) and (5), plotted to logarithmic co-ordinates, will be parallel straight lines having slope n. The intercept of (5) at $e_g = 1$ will be equal to $k(1 + \mu)^n$ and the ratio of the intercepts will be $\epsilon^{-\alpha}$. Thus the constants can all be found from the plate and grid current data for a composite diode characteristic and the value of μ, which may be determined in any of the usual ways.

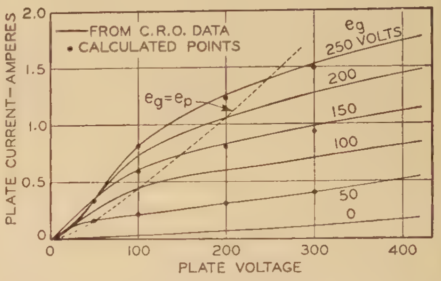

Figure 7. Positive-grid plate characteristic of type-46 tube, grid 2 connected to plate, showing comparison with calculated points

Figure 7 shows the agreement between equation (3), with constants determined by the composite diode characteristic, and an oscillographic measurement of the characteristics of a type-46 tube connected as a low-mu triode. The greatest error is less than ten per cent and occurs in a relatively unimportant part of the characteristic.

Grid Current

Subtracting equations (1) and (3) the grid current is found to be

$$i_g = k(e_p + \mu e_g)^n [1 - \epsilon^{-\alpha\, e_g/e_p}] \qquad (8)$$

When the constants for this equation are determined from the diode characteristic, it will hold very well for points near $e_g = e_p$ where the grid current is large. Although not nearly so accurate as the plate-current equation, the grid-current expression is a welcome aid in approximating the grid current and driving power in radio-frequency amplifiers.

Summary

It has been shown that the equation

$$i_p = k(e_p + \mu e_g)\epsilon^{-\alpha\, e_g/e_p}$$

will give values for the plate current of a triode in which the plate and grid are both positive, correct to within about ten per cent for a wide variety of tubes and voltages. The two most important approximations to which it is subject are (1) that secondary emission from the grid is negligible, (2) that the relation between $i_p/(i_p + i_g)$ and e_g/e_p can be represented by an exponential for any tube. Values for the constants in this equation were determined from a composite diode characteristic at low voltage and found to be accurate at much higher voltage and current. Finally it was seen that the grid current could be obtained approximately by taking the difference between this expression and that for the total space current.

This mathematical expression for positive-grid tube characteristics is extremely simple in form and sufficiently accurate for engineering purposes. It is valuable, because it avoids complicated and expensive oscillographic measurements of tube characteristics, and because it provides a new basis for attacking practical vacuum-tube problems.

Appendix A

Consider the path of a single electron which starts from some point on the cathode with negligible velocity. Its dynamical equations in rectangular co-ordinates will be

$$\frac{d^2y}{dt^2} = \frac{e}{m} E_y(x, y) \tag{1a}$$

$$\frac{d^2x}{dt^2} = \frac{e}{m} E_x(x, y) \tag{2a}$$

where $E_y(x, y)$ and $E_x(x, y)$ are scalar functions of the co-ordinates x and y, equal to the field intensity along the x and y axes, respectively. It is assumed that E_z is zero.

Equation (1a) may be written in the form,

$$d\left(\frac{dy}{dt}\right) = \left(\frac{e}{m}\right) E_y\,(x, y)\; dt \tag{3a}$$

or

$$\left(\frac{dy}{dt}\right) d\left(\frac{dy}{dt}\right) = \left(\frac{e}{m}\right) E_y(x, y)\; dy \tag{4a}$$

Integrating (4a)

$$\frac{1}{2}\left(\frac{dy}{dt}\right)^2 = \left(\frac{e}{m}\right)\int_{y_0}^{y} E_y\,(x, y)\; dy \tag{5a}$$

Similarly from equation (2a)

$$\frac{1}{2}\left(\frac{dx}{dt}\right)^2 = \left(\frac{e}{m}\right)\int_{x_0}^{x} E_x\,(x, y)\; dx \tag{6a}$$

Dividing (5a) by (6a)

$$\left(\frac{dy}{dx}\right)^2 = \frac{\displaystyle\int_{y_0}^{y} E_y(x, y)\; dy}{\displaystyle\int_{x_0}^{x} E_x(x, y)\; dx} \tag{7a}$$

Equation (7a) is the differential equation of the path of the electron, the time element having been eliminated. Now if the grid and plate potentials are increased or decreased in the same ratio, E_y and E_x will both be increased or decreased by the same constant multiplier, which may be removed from the integral signs and divided out. Consequently, for any tube the path of a single charged particle emitted by the cathode is a function only of the ratio of electrode voltages, and not of the magnitudes.

Nomenclature

i = current in amperes
i_g = grid current in amperes
i_p = plate current in amperes
μ = constant, amplification factor
k = constant, conductance factor
n = constant, space-charge exponent theoretically equal to 3/2
α = constant, distribution factor
e_p = plate voltage
e_g = grid voltage
e/m = ratio of charge to mass for an electron
E_y = y-component of electric field intensity
E_x = x-component of electric field intensity

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Discussion

Karl Spangenberg (Stanford University, Calif.): Mr. Porter is to be commended for a clear-cut presentation of the factors involved in the positive-grid characteristics of triodes.

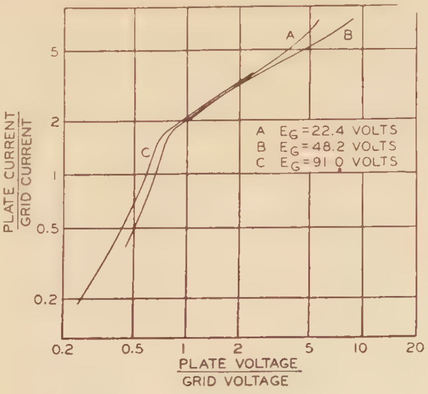

Figure 1

A limitation of the particular fundamental relationship assumed may however be indicated. The assumed relationship is of the form

$$y = e^{-\alpha x}$$

This form permits of the selection of but one parameter in fitting the empirical formula to the observed experimental data. That is, it is only possible to fit the empirical formula to the observed data at one point. Since a choice of ordinate and curvature are not independent in the assumed form the rest of the curve may or may not fit the experimental form.

The fundamental relationship assumed by Porter for the ratio of plate to space-current leads to an admitted error of considerable magnitude in the derived expression for grid current. This may be expected from the fact that while the diversion of a fraction of the space current to the grid is a second-order effect as far as plate current is concerned, it is a first-order effect for grid current.

A possible alternative basic relation is one of the form

$$i_p/i_g = f(e_p/e_g)$$

This form was proposed by early German investigators Tank[1] and Lange.[2] They showed that the functional form was a simple power of the ratio e_p/e_g for which the exponent has very nearly the value $^1/_2$ for all tubes. The coefficient, however, varies from tube to tube. This relation has been verified by the writer for small modern transmitting tubes.[3] Essentially the same result was arrived at independently by Myers.[4] This permits the use of the basic equation

$$i_p/i_g = \delta(e_p/e_g)^n$$

which permits the selection of two parameters, the exponent and the coefficient.

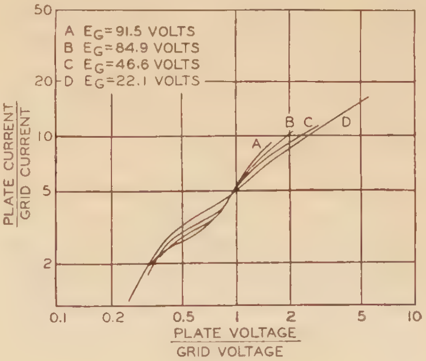

Figure 2

This form further expresses the relation in terms of the current ratio which experiences the greatest variation with voltage.

The coefficient and exponent in the above form are readily obtained by plotting i_p/i_g against e_p/e_g on log-log paper. The exponent is the slope of the straight-line characteristic obtained and the coefficient is the intercept upon the ordinate at $e_p/e_g = 1$. Such a plot is shown in figure 1. It will be observed that for values of e_p/e_g greater than one the curves are almost coincident straight lines with about the same slope which measures to be nearly $^1/_2$. It should be mentioned that no satisfactory theoretical explanation has as yet been given for the apparent universality of this value of the exponent in this region.

A further advantage of a plot of the type shown in figure 1 which may be mentioned is that it reveals readily any changes in the functional form which may occur in the ratio i_p/i_g. Such a change occurs in the curves of figure 1 for values of e_p/e_g of about 0.8. For values of e_p/e_g less than 0.8 the exponent as determined by the slope of the curves has a new value. The change to the new exponent occurs when the ratio e_p/e_g becomes sufficiently small so that some of the electrons which initially miss the grid are deflected strongly enough so that they are unable to reach the plate and fall back into the grid wires. For values of e_p/e_g greater than 0.8 all the electrons which initially miss the grid wires are received by the plate.

It should be pointed out that the coincidence of the curves in a plot like that of figure 1 depends upon the complete absence of secondary emission. Even the slightest traces of secondary emission will destroy the coincidence. Figure 2 shows the form of the curves for a tube with a slight amount of secondary emission. It will be observed that the curves are no longer coincident except in the vicinity of e_p/e_g where the exchange of secondary electrons between plate and grid tends to compensate. All of the curves given by Mr. Porter show considerable secondary emission by their similarity to the curves of figure 2 when plotted in that form. No satisfactory expression for current division in the presence of secondary emission has as yet been found.

It was not found possible to make the data of figure 1 fit Mr. Porter's equation because the value of α which made the curve have the proper value for $e_p/e_g = 1$ gave a curve whose curvature was much too small.

This is shown in figure 3 where the curves of figure 1 have been replotted for comparison. It is seen that the exponential function which matches the measured values for e_p/e_g equal to one is a poor fit for values less than this. If, however, an empirical curve of the form

$$y = 1 - kx^n$$

is used there are two parameters to select. A particular ordinate and curvature can be selected independently, and a much better fit to the observed values can be obtained. In this empirical formula the coefficient determines the intercept upon $e_p/e_g = 1$ and the exponent the curvature. This form permits the choice of the proper curvature from a whole family of curves with the required exponent.

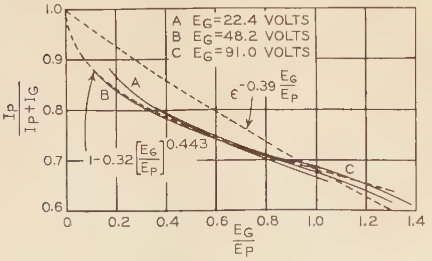

Figure 3

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2. H. Lange, *Seit. für Hochfrequenz.*, April 1928.

3. W. L. Everitt and K. Spangenberg, *Proc. I.R.E.*, May 1938.

4. D. M. Myers, *Proc.* Phys. Soc., May 1937.

R. W. Porter: Mr. Spangenberg is correct in pointing out the fact that there exists a very simple relation between the ratio of plate-to-grid current and the ratio of plate-to-grid voltage. In order to combine this expression with the space-charge equation in such a way as to obtain the plate current, however, it is necessary to perform manipulations which destroy some of the simplicity. The empirical form shown in figure 3 will not hold for very large ratios of grid-to-plate voltage since it indicates the possibility of negative plate currents.

In general all these expressions lead to difficult integrations when applied to radio-frequency design problems, so frequently it is of great advantage to have only one parameter involving division of current between grid and plate even if the empirical curve does not match the data perfectly at all points. The chief justification for permitting a certain amount of mismatch is that under normal operating conditions most of the plate and grid current will flow when the ratio of grid-to-plate voltage is nearly one. Hence the error in design calculations can be made small even when a single parameter is used. A second consideration is that secondary emission has a tendency to increase the ratio $i_p/(i_p + i_g)$ for small values of e_g/e_p and to decrease it for high values. Consequently any spreading of the curves shown in figure 3 as a result of secondary emission will be in the direction of the exponential curve.

Tests on and Performance of a High-Speed Multibreak 138-Kv Oil Circuit Breaker

By PHILIP SPORN
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The History and Results of High-Speed Breaker Development

HIGH-speed-oil-circuit-breaker development was really started in the period 1929–1930 and the first tests with high-speed 138-kv breakers were made at Philo in July 1930. The results of these tests, both from a breaker-design standpoint and from a system viewpoint, were described some seven years ago.[1] At that time it was definitely expected that operating benefits would be obtained out of the additional high speed but the problem of high speed was not yet then an acute or pressing one.

Parallel with that, although really anteceding that, was the development of high-speed relaying. This was first developed in what proved to be an impractical form in 1926. The original aim at that time was for a universal relay system that would operate, that is, would give an impulse to the breaker trip circuit within 20 cycles. The two developments went along in parallel although actual practical achievement in breaker speeds was attained much earlier than the relaying. However, by 1935 both achievements had been brought to such a state of perfection that it was entirely a routine matter to be able to get a six-to-eight-cycle 132-kv breaker in fairly standard construction and to get a relay system that would give universal protection in a period of one cycle or less. The history of the relay development has already been fully described.[2] By that time also the development in breakers had been carried through not only in the 138-kv classes but in the lower voltage classes as well. For special services, such as the Boulder Dam job, breakers of much faster speed were needed and three-cycle breakers of the impulse type were actually developed and built.[3]

Both of these developments have had the widest influence on the development

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[1] For all numbered references, see list at end of paper.

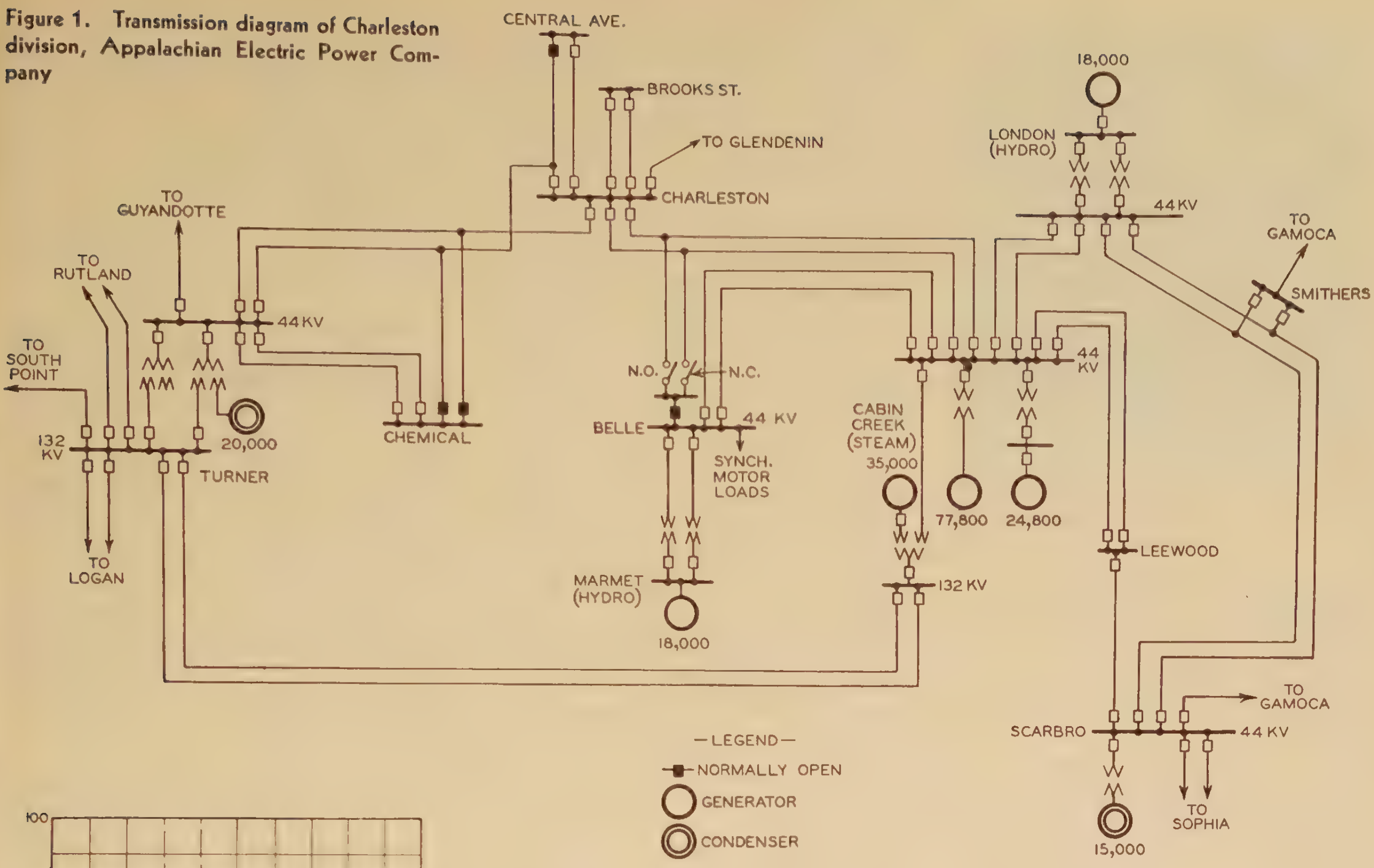
Figure 1. Transmission diagram of Charleston division, Appalachian Electric Power Company

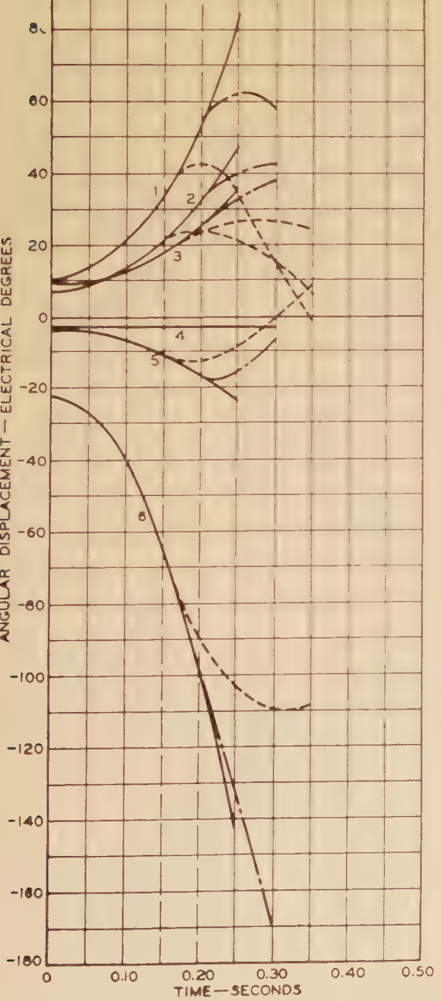

Figure 2. Swing curves from stability study of Charleston division

1—London
2—Marmet
3—Cabin Creek
4—Turner 132-kv system
5—Scarbro condenser
6—Belle motor load
——— Fault on
— — — Fault cleared by simultaneous opening of breakers in 0.20 second = 12 cycles
– – – – Fault cleared by simultaneous opening of breakers in 0.15 second = 9 cycles

and successful performance of modern transmission lines and networks. The effect on electric-power-system development and operation of these developments in breakers and relays can best be illustrated by a few typical examples of problems arising in transmission system operation and performance where the solution from a practical standpoint can be obtained only by a faster clearing of faults, which in turn can be obtained only by a high-speed breaker and in many cases only by a high-speed breaker coupled with a fast relay system.

Figure 1 shows a portion of the transmission system of the Appalachian Electric Power Company which operates in Virginia and West Virginia. This transmission system also extends to the affiliated companies, the Kentucky and West Virginia Power Company, Incorporated, and Kingsport Utilities, Incorporated, operating in Kentucky and Tennessee, respectively. The portion that is of particular interest is that part of the Charleston division lying between the Turner substation, which is west of Charleston, W. Va., and the Cabin Creek plant located at Cabin Creek Junction, W. Va., which is the principal steam plant serving that region and the immediately surrounding area. The loads in this territory are comparatively heavy, being predominantly coal and chemical operations. At the Belle substation, some six miles from Cabin Creek, a single load which some eight or nine years ago started at about 3,000 kw has now increased to approximately 42,000 kw, the principal use of power being in the operation of synchronous motors as large as 2,700 horsepower which drive high-pressure (1,200-atmosphere) compressors. Although some difficulty was experienced with surges in the early days when this load was building up, the problem seemed to have been entirely cleared up after an extensive investigation was carried out some five years ago, which showed the desirability of making some control changes on the motors and speeding up of the breakers on all the lines in the immediate neighborhood of the load.

About $2^1/_2$ years ago an additional source of generation was brought in almost directly on the bus bar of the main substation supplying this load. It was expected that this would have a beneficial effect on the stability of the supply system, but a series of disturbances that oc-

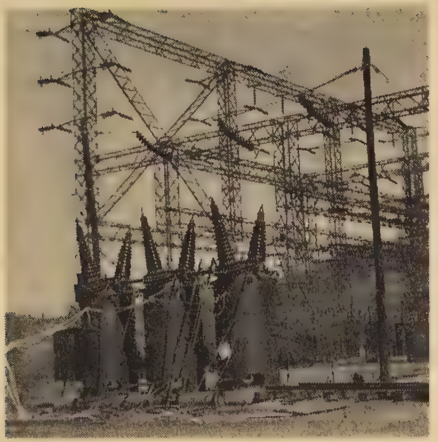

Figure 3. View of 138-kv oil circuit breaker set up for test at Philo, Ohio, November 1937

curred over the period immediately following the bringing in of the new generation source indicated that apparently the contrary had actually occurred. This led to a very thorough analysis of the system in the area and its performance under surge conditions, and this analysis very definitely showed that as was originally expected, the generating plant is aiding the system materially in maintaining the stability and voltage conditions, but that the growth of the large synchronous-compressor load had changed the complexity of the entire distribution problem so that a system of fault clearing that was adequate three years prior to the initiation of this trouble, was no longer adequate with the coming in of the new plant. The reason for this can be further seen from an examination of figure 2 which shows the performance of the various portions of the system for a fault at Cabin Creek on one of the two circuits running from Cabin Creek to this point. It will be noticed that the phase-angle displacements of the various portions of the system have been plotted against time from the initiation of a fault. At 0.2 second, that is at 12 cycles, the swing curve of the motor (curve 6) definitely shows the motors will fall out of step with the system. The rest of the system, that is the generating equipment at Marmet and at other points on the system, is a little shaky at this point but in all probability could ride through. On the other hand it will be clearly seen that by cutting the time 0.05 second, that is by decreasing the time only three cycles and reducing the maximum time of clearing of the fault to nine cycles (0.15 second) everything on the system, including the synchronous motors, will ride through the period of trouble in perfect safety. It is obvious that, granted a one-cycle relay system, the necessary maximum of nine cycles can be obtained only by a breaker having a time of eight cycles or less.

The above is a typical stability problem. Its solution was made possible by an eight-cycle breaker in combination with a one-cycle relay system. However, that is no guarantee that similar or other more

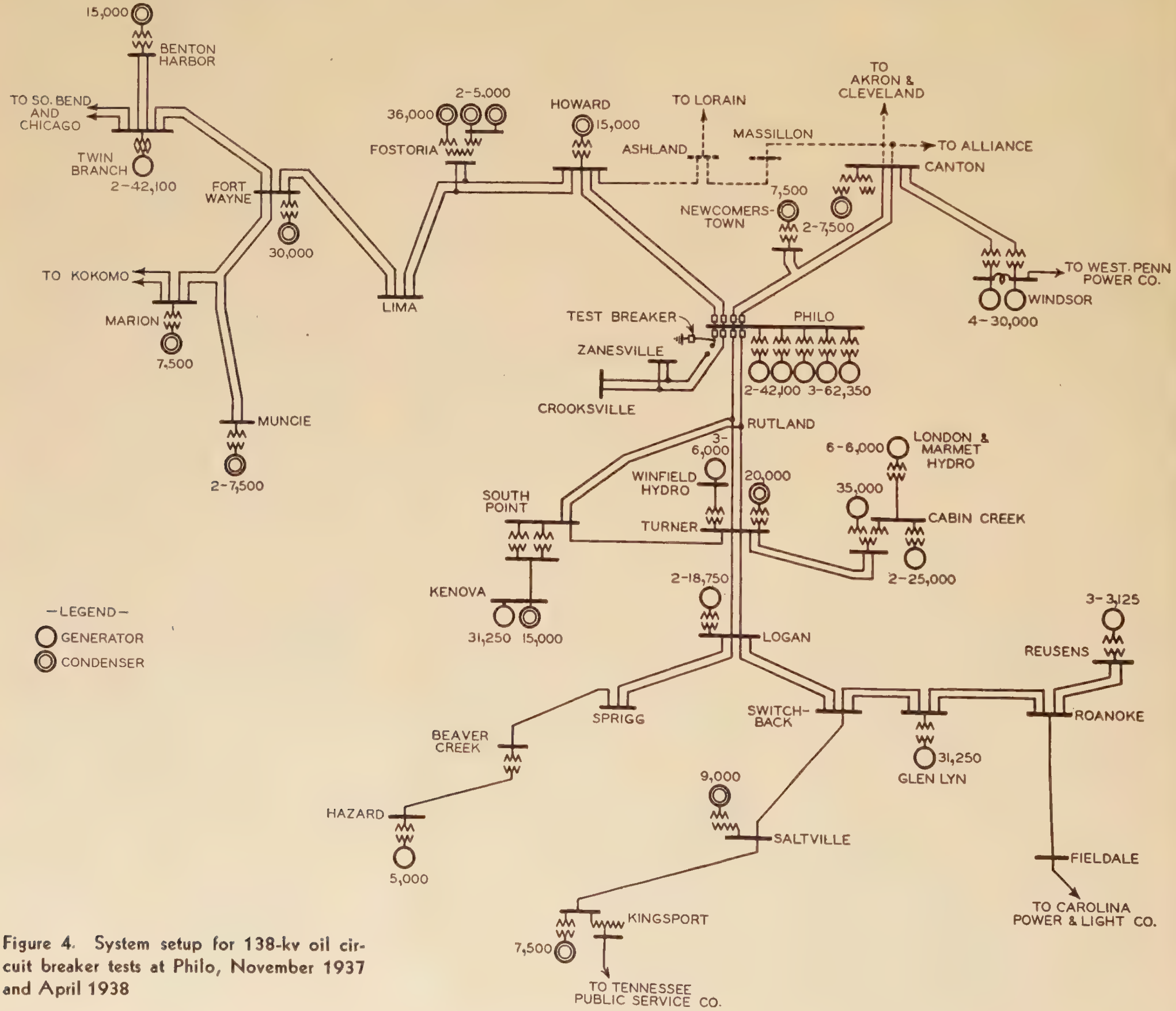

Figure 4. System setup for 138-kv oil circuit breaker tests at Philo, November 1937 and April 1938

involved problems in the future will not call for even faster time. If it is granted that one-cycle relay time is about as fast as can practically be sought, it is obvious that more breaker speed and speed beyond eight cycles is needed.

As a matter of fact such a need arose in connection with the development of ultrahigh-speed reclosing of transmission lines.[4] Here, although ultrahigh-speed reclosing was successfully accomplished on a breaker having very little better time than eight cycles, it was evident that the amount of waiting time with the line de-energized, necessary to bring about deionization, was not only a function of the arc current and the atmospheric conditions, but was also dependent upon the duration of arcing. Obviously if the arcing time was reduced, the total time necessary for reclosure would be reduced not only by that time but also by the additional gain as a result of the reduced waiting time needed with line de-energization.

A realization that the solution of many transmission problems, as typified by the two outlined above, was possible only by virtue of the fact that high-speed interruption was available when needed led to a decision some two years ago to apply the knowledge gained in the development of the impulse breaker to the development of a breaker having substantially higher speeds than appeared possible with the conventional oil blast breaker, and to do so along lines that would give the breaker no insurmountable economic handicaps in finding application on normal and commercial power systems. The results of that development are being described in the companion paper of Spurck and Strang.

Aims and Objects of Tests

The object of the tests herein described was basically to determine whether a breaker designed along the lines outlined[5] would successfully perform under the severe duty and test conditions that it was possible to set up at Philo. It was felt that in the light of the broad background of experience on breaker developments and tests obtained over a period of some 12 years, it was not safe to assume that the design difficulties encountered in making a change such as is involved in the development described could be overcome without thorough field testing. It was felt that these difficulties were so great that even with the fullest theoretical background and with the maximum amount possible in factory testing, it was not reasonable to expect even the most skilled designer to take care with finality of all the problems that were bound to arise. Hence the only safe basis of procedure, particularly since the equipment was protective equipment, was to subject the design to severe field tests and thus bring to light initial design errors and weaknesses. Past experience had indicated that those were almost inevitable and that designs put through the finishing developmental stages made possible by such tests were far more likely to operate trouble-free and completely successfully than those that were not subjected to the rigid experience of full field tests.

In short, it was hoped through this development and these tests to get a breaker having a time possibly close to four cycles in a design sufficiently simple, however, as to involve no appreciable, if any, increase in cost. Past experience had indicated that with a growing power system, having available such designs on an economical basis when they were actually needed was a material factor in maintaining not only reliability of system service, but in keeping system growth within economic limits.

System Setup for Tests

The Philo plant on the system of The Ohio Power Company provides the greatest concentration of power on the American Gas and Electric Company 132-kv system and was, therefore, chosen again, as in 1930, as the best place to test the new oil circuit breaker. As a matter of fact, the test breaker was set up in almost the same location with respect to the 132-kv switchyard as in 1930,[1] and it was connected in the same way to the transfer bus so as to make use of one of the Crooksville oil circuit breakers as a back-up breaker. A view of the breaker setup for test is shown in figure 3.

Likewise, the system setup as shown in figure 4 did not differ materially from that available for the 1930 tests, although a number of important system changes have been made since then. These include the double circuiting of the line from Philo all the way to Twin Branch, the installation of a 36,000-kva synchronous condenser at Fostoria, the placing in service of the hydro plants at London, Marmet, and Winfield, and the erection of a new 132-kv line from Turner to South Point. Except for the Howard line, which contributed substantially more current to the short circuit because of double circuiting, the effect of these changes in system setup and generation made very little difference in the short-circuit current contributions from these lines for a short circuit at Philo. At the Philo plant although the electrical end of the plant itself is exactly the same as in 1930, the actual short-circuit current supplied by the generators, as well as the total short-circuit current, was substantially greater due to the increased mechanical speed of the breaker and the consequent smaller decrement occurring prior to parting of the breaker contacts. This factor, together with the increase in system capacity mentioned above, made it possible to record tests as high as 2,000,000 kva based upon the initial current in the arc.

Description of the New Breaker

A detailed description of the design and theory of the new multibreak inter-

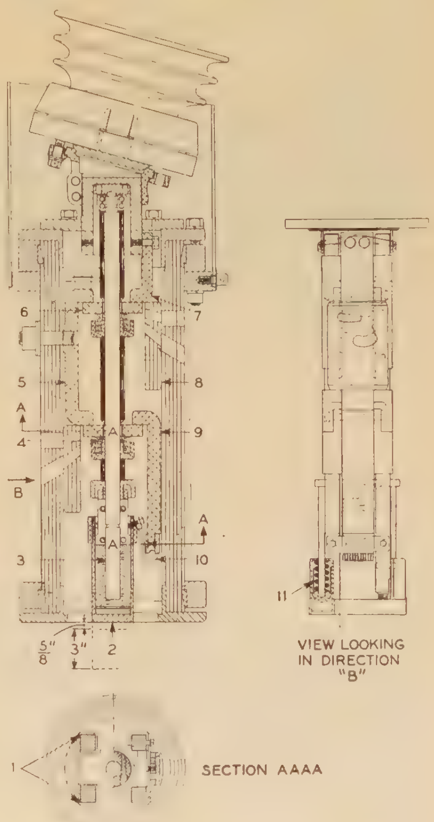

Figure 5. Cross section of multibreak, high-speed interrupter used in oil circuit breaker tested at Philo, April 24, 1938

1—Contact support rods
2—Contact cap
3—Springs
4—Contact pressure springs
5—Stationary contact bar
6—Movable contact
7—Stationary contact bar
8—Port segment
9—Stationary contact bar
10—Flexible connection
11—Opening springs

rupter, with particular reference to the six-break, 230-kv type, is given in the Spurck and Strang paper. The interrupters used in the test breakers at Philo were, of course, of the four-break design and were installed in a 138-kv conventional type of oil circuit breaker using standard 60-inch round tanks as shown in figure 3. A cross section of the interrupter itself is shown in figure 5, and a photograph of the interior parts alongside of the enclosing cylinder is shown in figure 6. The latter shows the general appearance of the interrupter, including the double-port opening in the side of the enclosing shell, whereas the cross section (figure 5) shows the arrangement of the four breaks, current carrying parts, location of port openings with respect to the interrupting breaks, and the compression springs along the central insulating rod.

The high-speed operating mechanism used on this breaker was similar to that shown schematically in figure 4 of the Spurck and Strang paper, except that it was designed for ultrahigh-speed reclosing, although most of the parts necessary for reclosing service were omitted. As shown in figure 3, this mechanism was mounted on the end of number 1 tank of the breaker.

Test Program and Results

Three series of tests, the first on November 20 and 21, 1937, the second on November 28, 1937, and the third and final series on April 24, 1938, were carried out on this breaker. This program may be summarized briefly as follows:

(*a*). Interrupters of the single-port design as described by Spurck and Strang were used in the first series of tests but failed to withstand the internal pressures developed in connection with currents somewhat above their rating.

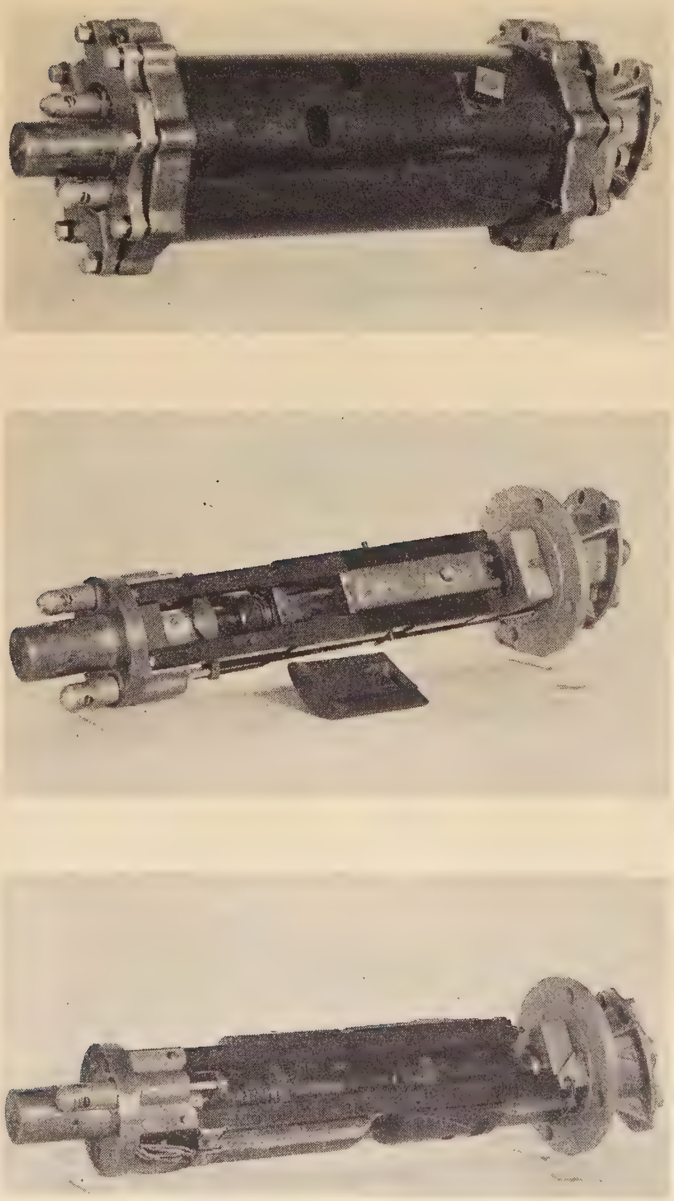

Figure 6. View of interior parts and enclosing cylinder of interrupter after tests at Philo, April 24, 1938

(*b*). In the second series of tests, using two poles only, one pole was equipped with single-port interrupters, while the second pole was equipped with double-port interrupters and larger total port area. As in the previous tests, the single-port interrupters failed to withstand the pressures developed at currents somewhat above their ratings, whereas the double-port interrupters performed successfully and the series of tests was completed on a single-phase basis.

(*c*). The third and final series of tests was carried out on a complete three-phase basis, using interrupters with double-port openings and substantially strengthened enclosing cylinders, together with other minor modifications. The breaker came through these tests in a completely successful manner.

Detailed results of these tests are given in tables I, II, and III covering the first, second, and third series of tests, respectively. These results will be described in more detail below:

Tests of November 20 and 21, 1937

As shown in table I, six preliminary tests were made, using one generator only, the first test primarily to check the test setup, and the other five with varying excitations on the generator to furnish information in connection with generator reactance characteristics. The remainder of the tests on November 20, included, first, a series of eight shots with two

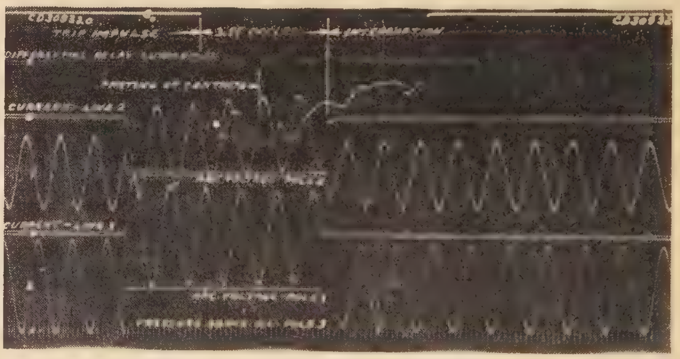

Figure 7. Oscillogram of test number 7, November 20, 1937, showing interruption of 1,500 amperes in 3.5 cycles

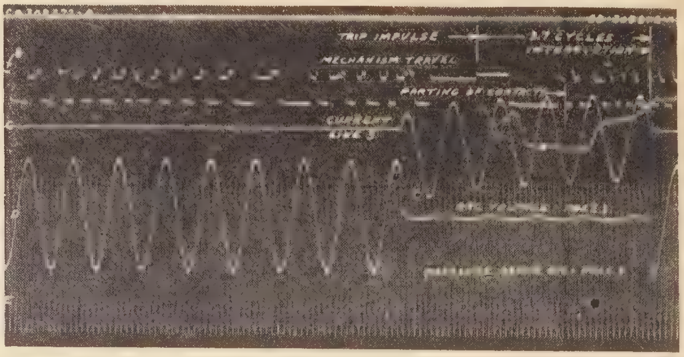

Figure 8. Oscillogram of test number 38, November 28, 1937, showing interruption of 8,500 amperes, single phase, in 3.7 cycles

Table I. First Series of Tests—November 20 and 21, 1937

Test Number	Type	Machines at Philo (Kva)		Lines Connected to 132-Kv Bus	Initial Current in Arc			Breaker Time (Cycles)			Equivalent Kva Interrupted	Remarks
					1	2	3	1	2	3		
1	O	1	42,100	None	1,000	940	990	Delayed tripping			230,000	Tests for generator reactance data
1A	O	1	42,100	None				Delayed tripping				
2	O	1	42,100	None	92	92	92	Delayed tripping			6,400	0.25 normal voltage
3	O	1	42,100	None	170	170	170	Delayed tripping			21,000	0.50 normal voltage
4	O	1	42,100	None	240	240	240	Delayed tripping			42,000	0.75 normal voltage
5	CO	1	42,100	None				Delayed tripping				1.00 normal voltage
6	O	1	42,100	None				Delayed tripping				1.10 normal voltage
7	O	2	42,100	None	1,500	1,400	1,200	3.7	3.5	3.4	360,000	Cleared OK
8	O	2	42,100	None	1,500	1,300	1,400	3.8	4.1	3.4	360,000	Cleared OK
9	CO	2	42,100	None	1,400	1,500	1,500	4.1	4.0	3.9	360,000	Cleared OK
10	CO	2	42,100	None	1,450	1,200	1,600	4.6	4.4	4.2	380,000	Cleared OK
11	O	2	42,100	1—Canton line open at far end	1,600	1,450	1,200	3.0	3.5	3.8	380,000	Cleared OK
12	O	2	42,100		1,200	1,400	1,600	4.2	3.6	3.4	380,000	Cleared OK
13	CO	2	42,100		1,300	1,350	1,350	4.3	3.7	3.9	320,000	Cleared OK
14	CO	2	42,100		1,200	1,400	1,300	4.3	3.7	4.0	335,000	Cleared OK
15	O	1	187,000	2—Howard, 2—Rutland closed to system	4,200	3,900	4,700	3.9	3.3	4.2	1,100,000	Cleared OK
16	O	1	187,000		4,300	4,300	4,200	4.2	3.6	3.9	1,000,000	Cleared OK
17	CO	1	187,000		4,500	4,000	5,300	3.1	2.5	1.5	1,270,000	Cleared OK Poor contact number 1 pole
18	CO	1	187,000		4,000	4,800	3,800	3.0	1.4	2.7	1,150,000	Cleared OK
19	O	1 1	187,000 42,100	All except Crooksville	6,500	6,700	6,350	3.5	3.4	3.8	1,600,000	Cleared OK Poor contact number 1 pole
20	O				6,800	6,700	6,300	3.6	3.5	3.3	1,620,000	Cleared OK
21	CO				5,900	7,800	6,600	6.0	0.5	0.3	1,860,000	Cleared OK. Heavy jar, poor contact number 1 and number 3 poles
22	CO	1 1	187,000 42,100	All except Crooksville	0	5,800	6,400		3.5	3.4	1,530,000	Cleared OK. No current number 1 pole. Poor contact number 3 pole Interrupter number 1 pole shattered on test number 21
23	O	1 2	187,000 42,100	All	0	0	8,000			3.6	1,900,000	Cleared OK. Tests number 3 pole only
24	..			All	0	0	7,600			3.2	1,820,000	Cleared OK
25				All	0	0	7,300			3.3	1,750,000	Cleared OK. Heavy jar. Interrupter number 3 pole shattered

generators only, including four tests with and four without a transmission line connected to the 132-kv bus to furnish a comparison between high- and low-voltage recovery rates. While the longest breaker time occurred with the high recovery rate setup where no lines were connected, the average results showed no consistent difference. This comparison, of course, was not particularly satisfactory because of the relatively low short-circuit current involved. It was not feasible to make such a comparison at higher levels of short-circuit current. All of these tests, 1 to 14, inclusive, in table I, were made on a setup completely isolated from the rest of the system.

Tests 15 to 18, inclusive, at a duty slightly above 1,000,000 kva, were carried out on November 21 without incident, with breaker time from less than two cycles to slightly over four cycles. On the next four shots, tests 19 to 22, inclusive, with slightly less than the full system capacity, the first two were entirely successful at approximately 1,600,000 kva, whereas test number 21 showed evidence of distress, and on test number 22 no current was obtained in phase 1 as a result of the complete shattering of one of the interrupters in that phase on the previous test. Three more shots were then carried out on a single-pole basis, the last of which at 1,750,000 kva destroyed one of the remaining interrupters, thus concluding the first series of tests.

Figure 7 shows an oscillogram of test number 7, a typical light shot of this series. The points at which tripping, contact parting, and interruption occurred and the actual breaker time are indicated on the oscillogram.

Tests of November 28, 1937

Between November 21 and November 28, two sets of interrupters sufficient to equip two breaker poles were reconstructed one with single-port openings approximately the same as on the initial tests, and the other with double-port openings and increased port area. As shown in table II, the interrupters with a single port, after withstanding four shots at light duty and two shots slightly above the full rating, failed on test number 32, causing mechanical damage to the interrupter and allowing arcing in that pole to continue for something more than thirty cycles until the back-up breaker opened the circuit. Subsequent examination of the interrupters in pole 2 indicated that electrical arc-over as well as mechanical damage had occurred.

Single-phase tests were then continued on the single pole with the double-port interrupters, concluding successfully a series of six with the full system capacity and a maximum recorded value of 2,000,000 kva on the last two shots. An oscillogram showing one of these last two heavy shots, test number 38, is presented in figure 8. As noted on the oscillogram, the opening time of the breaker in this case was 3.7 cycles.

Tests of April 24, 1938

While the series of single-phase tests on the double-port interrupters as completed on November 28, 1937, was entirely successful, nevertheless it was felt that, as a definite proof of the final design, it would be advisable to carry out a series of three-phase tests on the breaker equipped throughout with the double-port interrupters. This was particularly so since in the final interrupters, the designers, taking advantage of the information gained from previous tests, had made a number of modifications, such as increased strength of enclosing cylinders, improved electrical insulation, and other changes of a minor character.

The results of this final series of tests are shown in table III. These show that the breaker in its final form gave a most creditable performance. As shown in this table, after two preliminary shots with two generators only, the breaker was subjected immediately to four tests at duties between 1,400,000 and 1,500,000 kva, followed by six shots at the full system capacity, with a maximum of about 2,000,000 kva. As shown also in table III, on the last ten shots which were taken at duties from 1,400,000 to 2,000,-

Table II. Second Series of Tests—November 28, 1937

Test Number	Type	Machines at Philo (Kva)	Lines Connected to 132-Kv Bus	Initial Current in Arc 1	Initial Current in Arc 2	Initial Current in Arc 3	Breaker Time (Cycles) 1	Breaker Time (Cycles) 2	Breaker Time (Cycles) 3	Equivalent Kva Interrupted	Remarks
26	*O*	2 42,100	None	This pole not connected	1,800	2,000		3.7	4.0	480,000	Cleared OK
27	*O*	2 42,100	None		1,850	1,600		3.6	3.3	440,000	Cleared OK
28	*CO*	2 42,100	None		1,900	1,850		3.8	5.0	450,000	Cleared OK
29	*CO*	2 42,100	None		1,600	1,900		4.0	4.7	450,000	Cleared OK
30	*O*	1 187,000 1 42,100	All except Crooksville	This pole not connected	6,700	6,300		3.5	3.3	1,600,000	Cleared OK [pole 3
31	*O*				6,500			3.3		1,550,000	Cleared OK No oscillogram
32	*CO*				6,200	6,900			3.3	1,650,000	Arced to end of stroke on pole 2. Sustained oil spray from tank 2. Cleared by back-up breaker. Interrupters in pole 2 damaged
33	*O*	1 187,000 1 42,100	All except Crooksville	Poles 1 and 2 disconnected		5,900			3.3	1,400,000	Cleared OK Pole 3 only with doubleport interrupters on remainder of tests
34	*CO*					6,000			3.5	1,430,000	Cleared OK
35	*O*	1 187,000 2 42,100	All	Poles 1 and 2 disconnected		8,200			3.5	1,960,000	Cleared OK Added solid neutral ground to 2–63,000 kva banks not previously grounded. All other banks grounded throughout.
36	*CO*					7,700			3.9	1,840,000	Cleared OK
37	*O*					8,500			3.3	2,000,000	Cleared OK
38	*CO*					8,500			3.7	2,000,000	Cleared OK

000 kva, the breaker time varied from the maximum of 3.5 cycles to a minimum of less than two cycles. On the first two shots, however, which were made at light duty and, incidentally, at a high recovery rate, the breaker time, as would be expected, is somewhat longer. On shot number 2 this time reached a maximum of 5.7 cycles on pole number 2, which interrupted 1,400 amperes or the equivalent of 335,000 kva. Inasmuch as the duty in this case was actually less than 25 per cent of the breaker rating, the five-cycle speed rating of the breaker was, therefore, not actually exceeded under the prevailing standard rules for breaker rating. A typical oscillogram taken during this series of tests, showing the interruption on test number 8, is reproduced in figure 9.

The entire series of tests was carried out without any indication of distress, the only outward evidence of circuit interruption being the noticeable jar transmitted through the cinder-filled ground occupied by the test setup and a small amount of smoke or vapor issuing from the vent pipes on the tanks.

Following the tests, all of the interrupters were removed from the tanks for inspection and were found to be in excellent condition, showing no signs of distress whatever. A photograph of one of the interrupters taken after the completion of the tests is shown in figure 6. This is typical of all of the interrupters removed from this breaker. With the small amount of burning indicated on the contacts, it appeared that the interrupters could have withstood many more tests without maintenance or adjustment.

As would be expected, oil samples taken immediately after the tests showed no noticeable discoloration and tested an average of 30 kv, the same as at the beginning of the tests.

Effects of Tests on System Operation

In order to minimize the possibility of disturbances to customers during these tests, special arrangements were made to take care of certain areas electrically close to the Philo bus and thereby subject to the greatest voltage dips. The Newark area was taken care of by operating the Newark steam plant, tied in with the system only through a 66-kv line extending north to Howard substation and entirely disconnected from the normal 132-kv source at Crooksville. On the other hand, the town of Zanesville, which included among its factories a number of glass plants, which are generally particularly susceptible to voltage dips, had to be subjected to the full disturbance, as there was no other way to supply the town. Therefore, as a precautionary measure, the large industrial customers were notified as to the exact time of carrying out the shots with full system capacity in order that they could have operating men on hand to restart any motors which might possibly drop out because of some unforeseen contingency or because of, perhaps, some instantaneous under-voltage releases.

Except for these precautions, the effect of the tests on the system may be said to have been practically negligible as far as any harmful effects are concerned.

Conclusions

This entire program of field tests in connection with the development of this new high-speed interrupter has again demonstrated what was brought out in the beginning of this paper, namely, that no matter how skilled the designers may be, and with the most exhaustive research testing that is possible in factory testing laboratories, it is still necessary to look

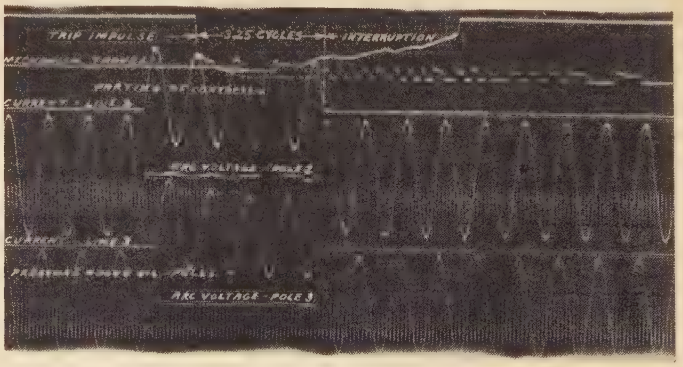

Figure 9. Oscillogram of test number 8, April 24, 1938, showing interruption of 7,700 amperes in 3.25 cycles

Table III. Third Series of Tests—April 24, 1938

Test Number	Type	Machines at Philo (Kva)	Lines Connected to 132-Kv Bus	Initial Current in Arc 1	Initial Current in Arc 2	Initial Current in Arc 3	Breaker Time (Cycles) 1	Breaker Time (Cycles) 2	Breaker Time (Cycles) 3	Equivalent Kva Interrupted	Remarks
1	O	2 42,100	None	1,600	1,400	1,500	3.6	3.6	3.7	380,000	Cleared OK
2	CO	2 42,100	None	1,600	1,400	1,300	4.2	5.8	5.0	380,000	Cleared OK
3	O	1 187,000	All except Crooksville	5,700	5,700	6,500	3.2	3.0	3.8	1,550,000	Cleared OK
4	O	1 187,000		6,000			3.5			1,430,000	Cleared OK. No record poles 2 and 3
5	CO	1 187,000		5,700	5,700	5,800	3.4	3.2	2.6	1,380,000	Cleared OK
6	CO	1 187,000		5,900	5,600	5,800	3.5	3.3	3.2	1,400,000	Cleared OK
7	O	1 187,000 2 42,100	All	6,700	7,100	7,400	2.9	3.2	3.0	1,760,000	Cleared OK
8	O			6,800	7,100	7,700	2.9	3.3	3.1	1,840,000	Cleared OK
9	CO			8,200	7,500	7,300	3.2	1.5	1.3	1,960,000	Cleared OK
10	CO	1 187,000 2 42,100	All	8,200	7,300	7,200	2.7	1.7	1.4	1,960,000	Cleared OK
11	CO			7,000	7,300	7,700	3.5	1.3	1.6	1,840,000	Cleared OK
12	CO			7,500	8,500	8,500	3.4	2.7	1.6	2,000,000	Cleared OK

to actual high-capacity field tests for ultimate confirmation of circuit breaker designs and to bring out possible weaknesses which otherwise may escape disclosure. In this particular development there is no question but that the fundamental design of the interrupter and, in general, its details had been worked out on a sound basis. It is no reflection whatever on the designers that unforeseen weaknesses were disclosed in the tests; on the contrary, it is proof of the soundness of the development that comparatively minor changes based upon the information obtained from the tests were all that were necessary to enable the final design to go through what is believed to be the most severe series of tests yet made on a high-voltage circuit breaker and do so with perfect performance.

It is also interesting to look at this development in the light of what has recently been said and written in considerable volume on the subject of oilless and oil-poor circuit breakers. A great deal of development work, largely abroad, but in an appreciable amount also in this country, has been going on in this field and many engineers have felt that such oilless or oil-poor breakers might eventually become the final answer to the circuit-breaker problem. Here we have, however, in an oil circuit breaker of the conventional type, the culmination of developments which have been carried along for some years in an orderly manner, resulting in a breaker which, with a rating of 1,500,000 kva, has demonstrated its ability to interrupt repeatedly and with no apparent effort, short circuits at and well above its rating, up to maximum values of 2,000,000 kva, with speeds consistently under four cycles. Viewed from this angle, we cannot help but feel that this development is truly a tribute to the level-headed skill and ingenuity of our American designers.

It goes without saying that the carrying out of tests of this nature represents not only an actual expense in time, construction, and even fuel cost, but also a considerable amount of stress and disturbance to the personnel operating a large power system. For all of this, however, we feel that we have been well repaid, first, because of the added confidence in the ability of the equipment and the system as a whole to handle disturbances smoothly gained by the operating forces and, second, for having been of assistance in putting the final necessary touches on a development which is without doubt a notable one, and one which will become of considerable value both now and in the future as a much needed tool in the development, expansion, and safe operation of large inter-connected power systems.

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5. **R. M. Spurck** and **H. E. Strang**, A New Multibreak Interrupter for Fast Clearing Oil Circuit Breakers, presented at the 1938 summer convention of the AIEE.

Discussion

J. B. MacNeill: See discussion, page 710.

W. F. Sims: See discussion, page 711.

S. B. Crary (General Electric Company, Schenectady, N. Y.): Power-system stability has been an important factor in determining the maximum allowable fault-clearing times. If we consider generator stability only and not load stability, total fault clearing times of the order of nine cycles for complete clearing of the fault appear to be adequate for even the most severe faults on the majority of power systems. Exceptions exist, of course, when the transmission distances are great and the steady-state power margins correspondingly low. However, fault-clearing times less than that calculated as the maximum allowable for generator stability are desirable in that a margin of safety is obtained which allows for unforseen extreme loadings and operation. Also the lower the switch time the greater the time or flexibility which can be allowed for relaying. In some cases this will allow for sequential switching out of the faulty section rather than requiring simultaneous switching.

The paper by Messrs. Sporn and St. Clair discusses a problem which it is believed will become of increasing importance. This is the ability to remove severe faults quickly enough so that important synchronous motor loads will not be lost. A synchronous motor is particularly liable to loss of synchronism for the following reasons.

1. When the fault is on, the synchronous motor tends to decelerate due to its shaft load and the losses due to the flow of fault current. This is not the case for a generator as the losses due to the flow of fault current decrease the acceleration and therefore are beneficial.

2. The size of the individual synchronous motors is usually small, so that the field flux decays more rapidly than in a generator due to the armature reaction created by the flow of fault current and the swing or oscillation after the fault is cleared.

3. The per-unit effective inertia of the rotating element is usually much less than that of generators. Exceptions exist, of course, for the case of high-inertia loads. This means that the angular displacement, in general, increases more rapidly.

4. Synchronous motors are not usually provided with voltage regulators. This combined with the low field time constant, reduces their synchronous strength appreciably during the period the fault is on and immediately after it is cleared.

5. Operators of industrial plants are not always cognizant of the stability problem or the importance of it, so they are apt to purchase and install motors which do not necessarily have high pull-out torques. A large group of motors of only ordinary characteristics or a motor connected through a long line to a system may have very little stability margin even under steady-state conditions.

All these factors combine to make the synchronous-motor load particularly susceptible to pulling out of step. A most effective manner to prevent their losing synchronism is by quick switching. Because of the nature of synchronous motor loads, the fault-clearing times for severe faults and locations relative to the synchronous motor load must be quicker than that required in general for corresponding severe faults relative to the generating station. Fault clearing times of less than nine cycles then become highly desirable.

If a power system has connected to it important synchronous-motor loads which require a high degree of service, then the need for very quick switching will undoubtedly exist for severe faults relative to the synchronous motor load.

L. F. Hunt (Southern California Edison Company, Ltd., Los Angeles, Calif.): The authors should be commended for their paper, and they should receive congratulations for their courage in pioneering actual system oil-circuit-breaker-short-circuit tests. The work involved in lining up a system for short-circuit tests is enormous, and the reading of a paper such as this really does not give the reader a full understanding of the intricacy of such tests.

The engineers of the Southern California Edison Company, Limited, agree with the authors that the final proving ground for oil switches is the actual system short-circuit tests. In fact, the latest policy has been to make system tests on breakers to ascertain complete information of their operation.

If I may digress from the paper a small amount, I would like to mention that we have conducted many tests on switches, and more recently have conducted about five series of tests on 230-kv breakers on our 220-kv system. Two series of tests were made on 230-kv breakers in accordance with the ones discussed in the paper, except having six breaks per pole instead of four. The first series was on April 25, 1937. The results of these tests read like a carbon copy of the authors' first series of tests November 20 and 21, 1937, except we were more fortunate in that we did not require the operation of a back-up breaker. Then on October 17, 1937, we ran the second series of tests with a much improved mechanical designed interrupter described in the Spurk and Strang paper. These tests also were successful, as in the case of the authors' third series of tests. You will note that our final tests were made prior to the authors' first test.

Just one question occurs to me. In the case of a failure on the test switch, how sure are you that the back-up breaker will take the rap and clear successfully?

Again, I wish to congratulate the authors and their men for the courage of these and other tests. The valuable information gained will give all switch users better switches.

D. C. Prince (General Electric Company, Philadelphia, Pa.): It seems appropriate to comment at this time on the debt of gratitude which switchgear manufacturers owe to operating engineers like Mr. Sporn, who have the courage and willingness to subject their systems to high-power field testing. A high-power test laboratory is a very expensive thing. The largest laboratories in this country have a symmetrical capacity a little over 500,000 kva and can deliver about 1,000,000 kva with a full offset wave. This is small compared with a 2,500,000-kva-rated breaker.

Various methods are employed to substantiate ratings beyond test plant capacity. These include pretripping, two-part tests, and other special arrangements. While there is good reason for having confidence in the data obtained from such tests, yet we all like to see how a circuit breaker behaves when it clears a fault on an actual system of large capacity.

Without field tests a new design may operate for months or years before its quality is tried by a real fault. The 287-kv transmission lines from Boulder to Los Angeles were so carefully protected by ground wires and counterpoises, and so well built that the circuit breakers were not called into automatic operation for nearly a year and a half. Then the flood came and there was a washout on both lines and the circuit breakers isolated the faulted sections with hardly a blink of the lights. When the actual emergency arose of course there was no oscillographic equipment hooked up so that no one knows what actually did happen.

The great power concentration around Philo actually delivered 2,000,000 kva to a fault which was cleared by the test breaker with all important events measured. Due to Mr. Sporn's courage and thirst for facts, we have an assurance of protection under actual operating conditions even though these conditions may include a catastrophe of nature such as the flood which damaged Boulder Dam–Los Angeles lines.

V. M. Marquis (American Gas and Electric Service Corporation, New York, N. Y.): A great many of us believe that the oil circuit breaker as an interrupting device represents a notable engineering achievement. To forcefully bring this out, it would be interesting to compare its performance with that of other methods of stopping the flow of energy, such as, for example, with a high-pressure valve, a brake, or a fire extinguisher. However, to make a comparison between the oil circuit breaker and other devices or mechanisms for interrupting the flow of energy is rather difficult. In the case of the oil circuit breaker, the actual energy in the arc is low, perhaps not more than 1,000 kilowatt-seconds. The power factor of the faulted circuit is probably ten per cent or less. Furthermore, the circuit breaker resorts to the trick of interrupting the arc when the current passes through zero. Granting all of this, it must be remembered that when the circuit breaker is attempting to extinguish the arc, the system voltage (in this case 132,000 volts) is at all times attempting to recover and although the current is interrupted when it passes through zero, it must be further borne in mind that the three phases do not open simultaneously, and therefore instantaneously there is an interchange of single-phase power (the mean of which is zero) between the phases which in kilowatts may possibly be equal to the kilovolt-amperes interrupted. All of this results in heavy forces which the oil circuit breaker must withstand because of the magnetic field and the making of room for the gas bubbles as fast as they are formed.

A comparison, although perhaps rather crude, might be made between the oil circuit breaker and the latest devices for extinguishing oil fires. We have made a rough comparison on this basis with some recent tests in which large oil fires were extinguished by means of water from high-pressure nozzles. The calculated equivalent of mechanical power represented by the fires in these tests, based on burning ten gallons of oil per minute, is approximately 25,000 kw, and the best performance obtained in putting out these fires was approximately 20 seconds. On this basis it is obvious that the circuit breaker compares most favorably in doing its job in three cycles or $^1/_{400}$ of the time taken to extinguish the fire.

This breaker is reported to have interrupted a 2,000,000-kva short circuit in approximately three cycles, and as shown by the film, a puff of smoke from the vents was the only visible sign that anything had happened. It may be of interest to compare this with the oil fire by showing a short section of film of the oil fire tests already referred to. Regardless of the accuracy of the comparison, I think we can all agree that the modern oil circuit breaker performs efficiently a most difficult job in an extremely short period of time.

Philip Sporn and **H. P. St. Clair:** In closing the discussion on this paper, the authors would like, first of all, to thank those who have contributed some very interesting and helpful discussions. It is particularly gratifying to find that these contributors have shown by their discussions, as well as by direct expression, that they fully appreciate the scope and importance of an undertaking such as that described.

Mr. Crary, we believe, has brought out the importance of high-speed switching in connection with the problem of stability involving synchronous-motor loads. We have already included in the paper some discussion of one such problem which was actually solved by speeding up circuit-breaker operation and we might say that there are many synchronous motor applications on almost any system which will, in general, be affected by the speed of switching. This problem, in fact, we consider to be one of the major arguments in favor of high-speed switching.

Mr. Sims shows a keen appreciation of the development work which has been done both by the manufacturers on this breaker and by our company in bringing this to a successful conclusion by means of test. In pointing out that the design of the new interrupter is such that it may be applied to replace corresponding parts of older breakers at a very great saving over the complete replacement of breakers, Mr. Sims has emphasized again the credit which we have given in the paper to our American designers for the progress they have made in improving the conventional oil circuit breaker along conventional lines.

We are very glad indeed to note from Mr. Hunt's discussion that the engineers of the Southern California Company, Limited, have arrived at the conclusion that the only reliable final proving ground for oil circuit breakers is actual short-circuit tests and that it is the policy of the company at the present time to make such tests on the system. As we have stated many times before, we are firmly convinced of the soundness of this position and we fully expect to continue making system short circuit tests whenever it is necessary to prove out a new

A New Multibreak Interrupter for Fast-Clearing Oil Circuit Breakers

By R. M. SPURCK
FELLOW AIEE

H. E. STRANG
ASSOCIATE AIEE

Synopsis: A description of a new multibreak interrupter for fast clearing of short circuits applicable to high-voltage conventional tank-type oil circuit breakers. Breakers equipped with such interrupters were subjected to interrupting tests on large 138-kv and 230-kv systems during which short circuits as high as 2,000,000 kva were interrupted in less than five cycles. The results of those interrupting tests are shown and discussed.

IT IS generally recognized that fast clearing of short circuits on power systems is desirable because among other benefits, shortening the duration of short circuits reduces the:

(*a*) Tendency of the system to become unstable.

(*b*) Magnitude and duration of voltage dips.

(*c*) Burning of the conductors at the point of short circuit.

(*d*) Potential damage to apparatus.

As the breaker interrupting time, that is, the time measured from the instant the trip coil is energized until the short circuit is interrupted, is an important part of the time required to clear a short circuit, much attention has recently been given to the development of breakers having short interrupting times. Most breakers sold today for all voltages and interrupting ratings, have a rated interrupting time of eight cycles, 0.133 second. Some few breakers for special applications have had interrupting time ratings of three cycles, 0.05 second. Breakers of that time rating, utilizing the impulse oil-blast principle in which oil is forced between the contacts by a mechanically driven piston, are used on the 287.5-kv transmission line between Boulder Dam and Los Angeles[1] and on the 138-kv side of the autotransformers of the Los Angeles end of that line. Also, many single-phase impulse oil-blast-type breakers having an interrupting time of one cycle, 0.04 second, are in operation on 11,000-volt single-phase 25-cycle railway service.[2] During the last two years, a need appeared for breakers of a time rating intermediate between that of standard breakers rated eight cycles and that of the special very expensive breakers rated three cycles. When the possibility of meeting this need was reviewed, it was natural to try to adopt, as far as applicable, the principles already established in the superspeed high-voltage impulse breakers. Pressure-generating breaks[3] were selected as the driving force for the oil blast rather than the mechanical driven piston of the impulse breaker. This method has the proved reliability of thousands of applications. In the absence of extreme speed requirements, this self-generated oil-blast action seemed to be fast enough.

High-voltage multibreak impulse breakers use a cylindrical insulating interrupting chamber in which a number of interrupting contacts connected in series are placed adjacent to port openings in the cylinder wall. The logical modification in such an interrupter to utilize the arc-pressure oil-motivating means was to associate a pressure-generating gap with each interrupting gap.

It seemed expedient to make such interrupters adaptable to conventional tank-type breakers because; first, it permitted the use of conventional bushing current transformers in place of the more expensive self-contained tripping transformers required by the high-voltage impulse breaker, and second, it made possible the modernization of large numbers of circuit breakers already installed so that operators could secure faster operating time without the expense of completely new apparatus.

Several different designs of multibreak interrupters of cylindrical shape adapted to tank-type breakers and utilizing the cross-blast principle with self-contained pressure generation, were subjected to interrupting tests at the high-capacity testing station at Schenectady. From those tests, the number of breaks required for various voltages was determined and the best features of all the types, such as shape, number, and location of port openings, were combined in arriving at a design which would interrupt effectively in minimum time.

Interrupters of the above described general design were subjected to many

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R. M. Spurck is manager of sales, circuit breaker section, General Electric Company, Philadelphia, Pa.; H. E. Strang is managing engineer, large oil circuit breaker division of the same company.

[1] For all numbered references, see list at end of paper.

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development in which we are interested.

In regard to Mr. Hunt's question as to how sure we are that the back-up breaker will take the rap and clear successfully in case of a failure on a test switch, the final answer to this question is that we are not positively certain. However, the back-up breaker used is one that has been in service and has performed successfully on many previous occasions during normal system operation and we have a fairly high degree of confidence that it will interrupt the short circuit. For one thing, the duty on the back-up breaker in such an event would be appreciably less than that involved in a quick clearing of the test breaker because of the longer time and resulting decrement. But, and this is more important, since the back-up breaker is one of the regular breakers on which is placed dependence for normal protection of the system, we feel there should be no question regarding its ability to handle the duty imposed upon it and if it is not capable of doing so, there really is no better time to find it out than under staged short-circuit conditions when everyone is on his toes and prepared for whatever may happen.

Mr. MacNeill has brought out a number of interesting points, particularly in comparing the present interrupter with the multibreaker design used in the Boulder Dam 287-kv breakers. Since most of these points have to do mainly with design details, I shall leave them for the consideration of the authors of our companion paper, Messrs. Spurck and Strang. Such discussions are always helpful in clarifying ideas and theories in connection with new developments.

Mr. Prince has pointed out that the circuit breakers installed on the Boulder Dam–Los Angeles 287-kv transmission line were not called upon to operate on a short circuit for nearly $1^1/_2$ years after installation. While we are not nearly so fortunate on our own system in having such infrequent faults, at the same time circuit breakers may wait a long time for anything like a severe test, first, because interrupting capacities are usually figured on a more or less future setup and, second, because even though faults may occur frequently enough, the location of these faults is rarely such as to give rise to the maximum possible fault current. This only confirms the wisdom of making system short-circuit tests to find out before one is lulled into a false sense of security and before there is a chance of an expensive failure, whether a given circuit breaker or circuit-breaker design is capable of performing as it is expected to perform.

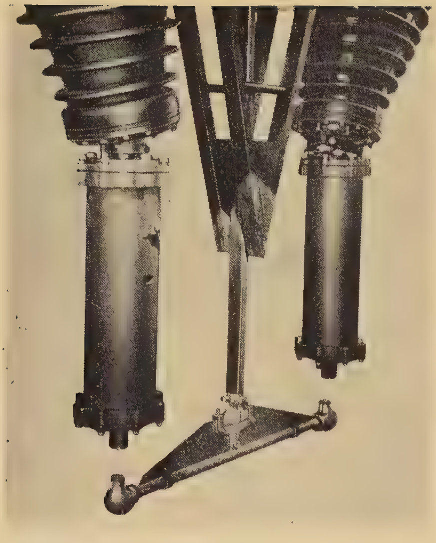


Figure 1. Six-break single-port interrupters installed on a 230-kv oil circuit breaker

interrupting tests at low currents and high currents in the Schenectady testing station. They were also given preliminary field tests before the final design was submitted for the field tests at Saugus and at Philo herein described.

In the tests at Schenectady, attention was not centered alone on the ability of the interrupters to handle heavy short-circuit currents but also on the ability to interrupt light currents as well. For example, the six-break interrupter was tested successfully on currents ranging from 20 amperes to 12,000 amperes and the four-break design from 25 amperes up to 27,000 amperes.

From those tests, it was determined that six breaks per terminal, that is, three pressure generating and three interrupting breaks, were adequate for 230 kv applications and four breaks for 138-kv service without resorting to voltage grading other than that resulting from the normal arrangement of parts.

Multibreak interrupters with cross-blast oil flow not requiring a mechanically driven piston for oil motivation and applicable to conventional tank-type high-voltage breakers are now available for breakers, or the modernization of breakers, rated from 115 kv to 230 kv in interrupting ratings up to 2,500,000 kva.

Description of Interrupter

A pair of these interrupters attached to one pole of a 230-kv oil circuit breaker is shown in figure 1. In figure 2 the interrupter is shown in cross section.

The main housing of the interrupter is a thick walled cylinder of insulating material having an unusually high dielectric and mechanical strength. This insulating housing is readily removable without removing the interrupter from the bushing. Figure 3 shows a six-break interrupter with housing removed and partially disassembled. When the housing is removed, all contact parts are still in place but exposed for inspection. Stationary members of the conducting parts are supported on four vertical insulating posts, each fastened at the top to the upper cover of the interrupter, and at the bottom to a retainer. Extending through the center of the interrupter is an insulating rod which carries the moving contacts. This insulating rod, which projects out of the lower end of the interrupter, terminates in a metal cap which is the contact engaged by the crosshead. A flexible lead from this cap carries the current from the cap to the main current path of the interrupter. Heavy pressure for each contact is obtained by inserting a spring between each contact and its fastening to the center operating rod. Interrupting contact faces are of Elkonite which is outstanding in its ability to withstand severe and repeated arcing with minimum loss of material.

Table I. Approximate Short-Circuit Values Obtainable by Variation of System Currents

Setup	Line to Ground Short-Circuit Current (Amperes)	Equivalent Three-Phase Kilovolt-Amperes
1	1,000	375,000
2	1,400	525,000
3	2,700	1,000,000
4	4,500	1,700,000
5	Line charging current approximately 50 amperes	

NOTE: Setup 1 utilized a feed from the 66-kv system through step-up transformers at Saugus to 220 kv. All other test arrangements, including that for line charging current, used lines of the 230-kv system only.

When the breaker opens, the crosshead moves downward thus permitting a spring inside the interrupter to force the center rod supporting the interrupting contacts downward and part the contacts inside the interrupter. The arcs formed in the interrupter decompose oil into gas which creates pressure and forces oil out through the ports. The ports are so located in relation to the contacts that the flow of oil is directed between the contacts. Thus, during the time current is flowing, both oil and gas are flowing out of the port. As current zero is approached, less gas and more oil are carried over the contacts and out the port. It is important to bring out that the bleeding of gas from the interrupter takes place at the contacts adjacent to the port. Gas created at the contacts which have no port adjacent to them is stored in the chamber so that at current zero when no gas is generated, the stored pressure inside of the chamber is sufficient to drive oil into the space between the contacts adjacent to the port. Only a small contact separation is required, therefore, to allow sufficient oil insulation between the contacts to prevent the recovery voltage from breaking down the di-

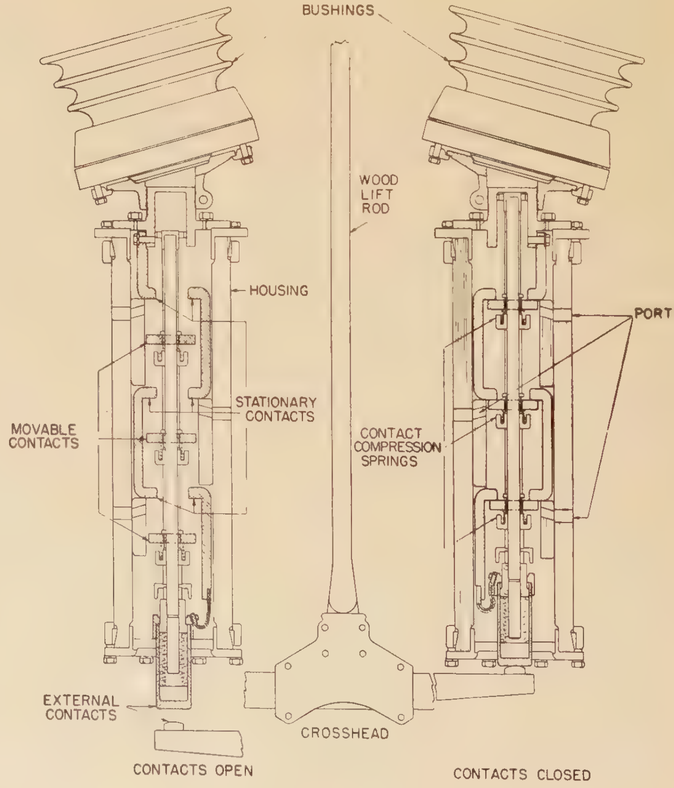


Figure 2. Cross section of six-break single-port interrupters for 230-kv oil circuit breakers. Contacts shown in open and closed positions

Table II. Interrupting Tests on a 220-Kv System

Test Number	Initial Voltage (Kilovolts)	Number of Ports Per Break	Tank	Duty**	Current Interrupted (Root-Mean-Square Amperes)	Equivalent Three-Phase Kilovolt-amperes	Breaker Interrupting Time (Cycles*)
1	216	1	*A*	Opening	1,032	386,000	4.22
1*A*	216	1	*A*	CO	1,010	378,000	3.74
2	216	1	*A*	Opening	1,414	529,000	3.57
2*A*	216	1	*A*	CO	1,414	529,000	3.44
3	216	1	*A*	Opening	2,680	1,000,000	3.5
3*A*	216	1	*A*	CO	2,680	1,000,000	3.27
4	216	1	*A*	Opening	4,400	1,640,000	2.96
4*A*	216	1	*A*	CO		1,760,000†	
15-second interval between tests 4A and 4A-1							
4*A*-1	216	1	*A*	CO	4,700	1,760,000	1.37
5	216	1	*C*	Opening	4,800	1,800,000	3.05
5*A*-1	216	1	*C*	CO	4,550	1,700,000	2.15
15-second interval between tests 5A-1 and 5A-2							
5*A*-2	216	1	*C*	CO	4,550	1,700,000	1.96
6	216	2	*B*	Opening	4,600	1,720,000	3.1
6*A*-1	216	2	*B*	CO	4,700	1,760,000	2.89
15 second interval between tests 6A-1 and 6A-2							
6*A*-2	216	2	*B*	CO	4,700	1,760,000	2.45

* 50-cycle system.

** Opening means breaker initially in closed position and tripped on occurrence of fault. CO means breaker is closed on a fault and then tripped open.

† No record. Estimated value.

electric between the contacts. This interrupting action is entirely in accordance with the oil-blast principle of interruption.

Proper arrangement of the port or ports in relation to the contacts results in an effective device which interrupts the current at an early current zero after the contacts part, as shown in the results of the field tests. Interruption of the circuit generally occurs before the crosshead contact parts from the exterior contact at the bottom of the interrupter. After interruption, the crosshead moves downward to the full stroke of the breaker, a distance sufficient to withstand the required insulation tests with the breaker in the open position.

Field Interrupting Tests at Saugus

On October 17, 1937, at the Saugus substation of the Southern California Edison Company, Ltd., a series of interrupting tests at 220 kv, frequency 50 cycles, was made on multibreak interrupters of the self-pressure-generating cross-blast type installed in a rebuilt triple-pole 230-kv type *FHKO*-139 oil circuit breaker having 108-inch-diameter round tanks. This oil circuit breaker was supplied in 1929. When originally put in service, it was equipped with plain explosion chambers for arc control and had an interrupting rating of 2,500,000 kva on the then standard CO–2 minute–CO duty cycle.

When tested, each pole of the breaker was equipped with six-break multibreak interrupters. Tanks *A* and *C* were provided with interrupters having single ports adjacent to each break and tank *B* with double ports. The original centrifugal-type closing mechanism was replaced by a cam-type mechanism of new design. This cam mechanism closes the breaker in about one-half second as compared with a closing time of about one second required with the original mechanism. Clear break distance from the external contact of each interrupter to the crosshead contact, with the breaker in the open position, was 32 inches. The six gaps of each interrupter add approximately 20 inches to that clear-break distance thus making the total clearance 52 inches from the live part of the lower end of the bushing to the crosshead in the open position.

Cam mechanisms for the operation of high-voltage breakers, are a recent development designed to improve on solenoid and centrifugal motor-type mechanisms in the following respects:

(*a*) Faster closing, or shorter closing time.

(*b*) Better proportioning of the driving output of the mechanism to the load requirements of the breaker.

(*c*) Lower operating currents for the same duty.

(*d*) Reducing slam and overtravel at the end of the closing stroke.

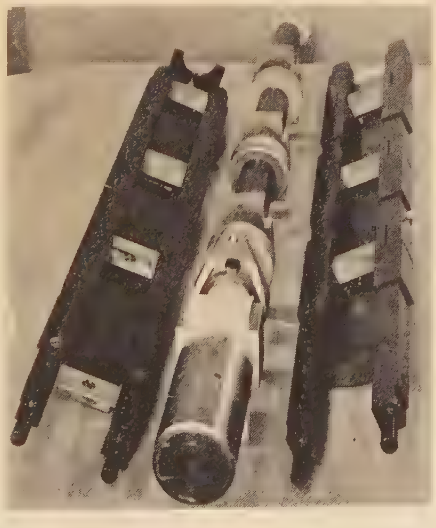


Figure 3. Six-break interrupter for 230-kv oil circuit breakers with housing removed and partially disassembled

Figure 4 shows a diagram of a cam motor mechanism of the type used on the test breaker. The driving element of this mechanism consists of a specially designed high-starting-torque motor arranged to rotate a cam approximately 270 degrees through a spur-gear reduction. Such a driving unit is substituted for the solenoid coil and plunger of solenoid mechanisms, thereby utilizing the same simple and reliable linkage used on modern solenoid mechanisms and retaining the feature of being mechanically trip-free in all positions. Tests show that these mechanisms which combine the features of the present improved solenoid linkage with the motor-driven cam, eliminate the slow starting of solenoids caused by the slow current build up and permit proportioning of the cam in accordance with actual output requirements. The result is the attainment of the objectives noted above.

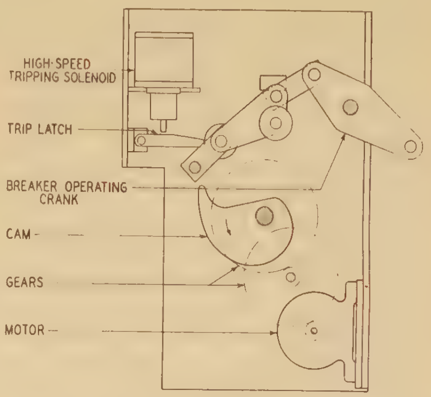


Figure 4. Diagram of cam-type operating mechanism for oil circuit breakers

The Saugus substation is a switching station for 66-kv and 230-kv lines. Oil circuit breakers and disconnecting switches in the station are so arranged that various lines entering the station can be connected individually or in combination to the test breaker in such a way that single-phase line-to-ground short circuits on the 220-kv system would produce approximately the equivalent three-phase values shown in table I.

All of the tests were made in one day.

No inspection of contacts or adjustments were made during the tests. Table II shows the results of the interrupting test, table III the charging current tests. The oil in all tanks tested at 30 kv between one-inch-diameter flat disks spaced 0.1 inch apart at the beginning of the tests and also at the conclusion of the tests. Oil color remained substantially unchanged during the tests. In order to check the condition of the contacts as the tests progressed, contact resistance measurements were made at frequent intervals during the tests. These tests were made by measuring the voltage drop across the breaker pole at currents of 400 amperes and 600 amperes. No change in contact resistance was indicated during or after the tests. Examination of the interrupters after the tests showed that they were substantially in the same condition as when installed. There was slight burning of the fiber burning plates opposite the contacts but the ports themselves had only slight discoloration over a part of their surface. Some insulation re-enforcing barriers were displaced because of inadequate holding screws which can easily be strengthened in future designs. Contacts were only slightly burned, as shown on the photograph of representative contact samples, figure 7. This contact burning is considered so minor that it is estimated that the contacts could have been subjected to ten times as many operations without impairing their current-carrying ability.

Oscillograms recording current, voltage, crosshead travel, trip coil current, etc., were taken for all short-circuit tests. Short-circuit currents transformed by a bushing-type current transformer and by a conventional wound transformer, were recorded on the oscillograph. The currents indicated by the bushing current transformer were, in general, slightly higher than those indicated by the wound transformer. Values shown in table I are calculated from the currents registered from the bushing-type transformer. The oscillogram of test 5*A*-2 shown on figure 5, is typical of those obtained on the short-circuit tests. This test is of particular interest in that it represents a CO test during which 1,700,000 kva was interrupted and which was made 15 seconds after test 5*A*-1 a CO operation interrupting 1,700,000 kva. In this latter test, the total time of short circuit was 2.56 cycles from the time the short circuit was established to interruption, including relay time.

Line-charging-current test oscillograms included records of voltage, crosshead travel and the charging current in each of two lines. Oscillogram of test Number 8, an opening operation designated as figure 6, is representative of the line charging current tests. Although the oscillogram tells its own story, it is not considered superfluous to call attention to the disappearance of the normal-frequency current and the appearance of high-frequency high-current oscillations in the oscillograph line-current record after the breaker contacts parted. Furthermore, although the breaker interrupting time when interrupting line charging current (maximum recorded value 3.88 cycles) was longer than the breaker interrupting time on large short circuits, it was, nevertheless, slightly shorter than the interrupting time of the CO tests on short circuit of approximately 386,000 kva on which the breaker operating time was 4.22 cycles and which was the maximum value recorded for any test.

Two series of 138-kv field tests were made on the four-break interrupters at the Philo station at The Ohio Power Company. The details of these tests including a description of the system setup and a tabulation of results are given in a companion paper by Sporn and St. Clair.[4]

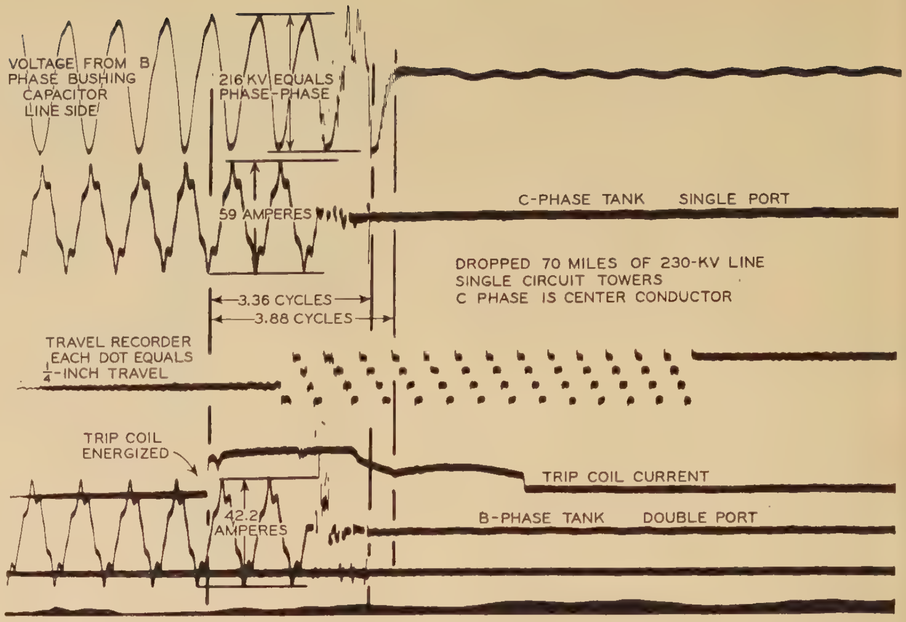


Figure 6. Oscillogram of test number 8 recording interruption of line charging current of 70 miles of line

Line voltage—216 kv
Current phase *B*—42.2 amperes
Interrupting time phase *B*—3.88 cycles
Current phase *C*—59.0 amperes
Interrupting time phase *C*—3.36 cycles
50-cycle system

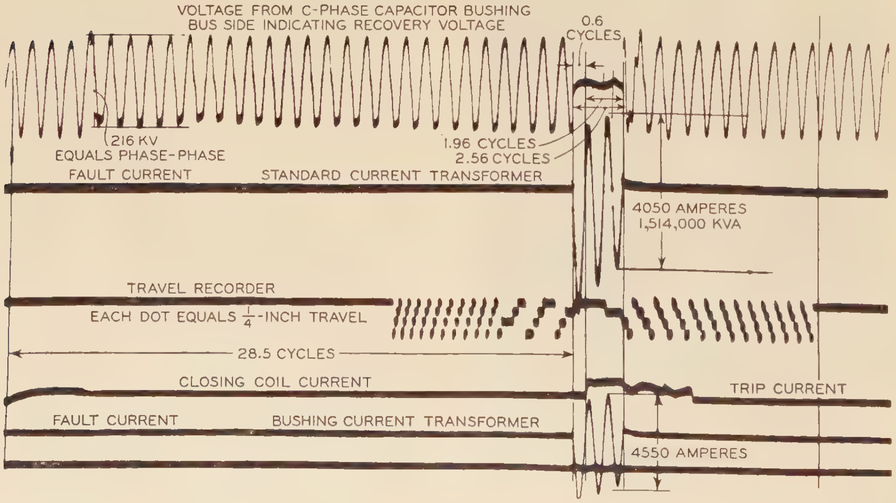


Figure 5. Oscillogram of test number 5A-2. Test breaker closed on, and interrupted a short circuit of 1,700,000 kva at 216 kv. Breaker interrupting time 1.96 cycles, total short-circuit duration 2.56 cycles. 50 cycle system

Table III. Line-Charging-Current Interrupting Tests on a 230-Kv System

Test Number	Kilovolts	Number of Ports Per Break	Tank	Kind of Test	Line Charging Current (Amperes)	Breaker Interrupting Time (Cycles*)
7	216	1	*C*	Opening	43.2	3.08
7	216	2	*B*	Opening	57.0	3.08
8	216	1	*C*	Opening	59.0	3.36
8	216	2	*B*	Opening	42.2	3.88
9	216	1	*C*	Closing	57.6	
9	216	2	*B*	Closing	43.2	
10	216	1	*C*	Opening	No record**	
10	216	2	*B*	Opening	No record**	

* 50-cycle system.
** Same connections as for previous tests.

In brief, the tests were made on a new 1,500,000-kva 60-inch tank breaker equipped with a new high-speed trip cam mechanism and four-break interrupters which, in turn, were built with single port openings adjacent to each interrupting break and of somewhat lighter construction than those used on the circuit breaker tested at the Saugus substation. Twenty-one three-phase tests were made both opening and closing-opening (CO) at capacities ranging from 239,000 to 1,860,000 kva with no delay or inspection. Although the twenty-first test cleared the circuit without distress, it was found on the next test that one pole was open-circuited due, as found by later inspection, to a ruptured cylinder occurring on the twenty-first test.

After disconnecting two poles, including the damaged one, the tests were continued single phase to ground on one pole until on the twenty-fifth test at 1,910,000 kva, or 25 per cent above the rating of the breaker, the interrupters in this pole also suffered mechanical damage. However, the breaker interrupted the circuit in the normal time of 3.3 cycles with no outward evidence of distress.

Although these tests indicated gratifying performance at capacities considerably above the breaker rating and with maximum operating time of 4.6 cycles, it was considered quite obvious that certain modifications and additional tests would have to be made. Accordingly, after making two modifications in the interrupters—(1) increased size of vents to reduce pressures at high currents; and (2) slight rearrangement of insulating parts to obtain better arc control, a second series of tests was carried out on two poles only of the three-pole breaker, one pole equipped with interrupters modified by having two port openings, instead of one, adjacent to each interrupting break. These extra openings provide additional venting to relieve the pressure inside the cylinder, and at the same time the wall between them acts as an arc splitter, the efficacy of which has been demonstrated previously. The other pole was equipped with single port interrupters substantially the same as in the previous series of tests. After six two-phase-to-ground tests, going to values above the rating of the breaker, the single port interrupters again suffered mechanical damage and the tests were continued single phase to ground on the double port interrupters, completing the schedule of 13 tests without further trouble. In all of these 13 tests at duties from 382,000 to 2,030,000 kva, the maximum interrupting time was five cycles and out of the nine tests which were above 1,400,000 kva, the maximum time was 3.9 cycles. After these tests, the oil showed only slight deterioration, and, as in the case of the Saugus tests, the Elkonite-surfaced contacts showed practically no burning nor did any of the other parts of the interrupter show any deterioration or signs of distress.

Since 1926, three major series of oil-circuit-breaker interrupting tests have been made on the 138-kv system of the Ohio Power Company. Figure 8 compares the results of these three series of tests and shows a reduction in oil-circuit-breaker interrupting time that has been realized since the first series in 1926. Figure 8 also gives an indication of the increase in power concentration on the system. During the tests made in 1926 at Canton,[5] a circuit breaker equipped with plain explosion chambers interrupted up to 750,000 kva at 138 kv in 15 to 20 cycles. This represented a marked improvement in performance over the plain break contacts of an earlier day. By 1930,[6] about 1,750,000 kva was available for field testing at Philo, and oil blast chambers gave over-all operating times of eight cycles or less. In 1937, the system short circuit had grown to over 2,000,000 kva, providing the largest amount of power ever made available for oil circuit breaker field tests. During these tests, the double-port multibreak interrupter successfully cleared all currents over this range with a maximum breaker interrupting time of five cycles. Contrary to what might be expected, there is scarcely any measurable difference in breaker interrupting time of the single and double port interrupters.

Figure 7. Representative contacts of interrupter after tests at Saugus substation

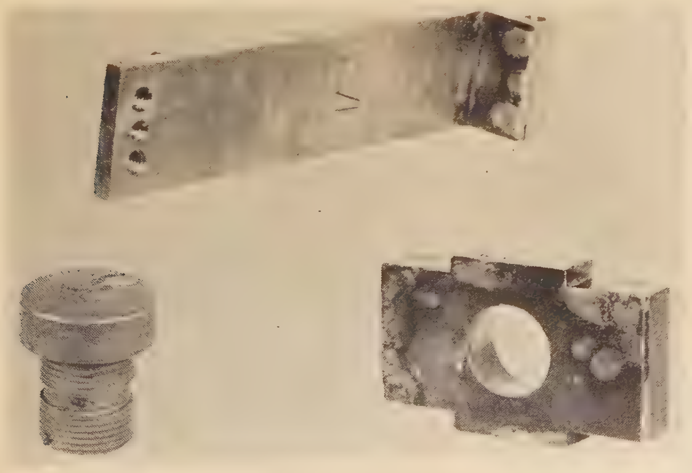
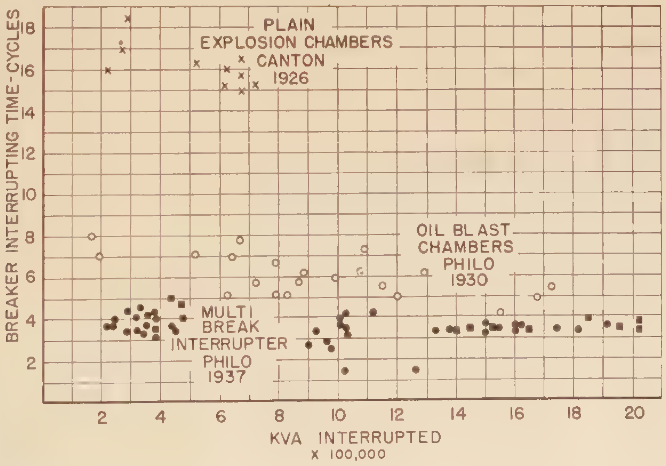


Figure 8. Comparison of oil circuit breaker interrupting time as shown by tests on a 138-kv system

Dark circles—single ports
Dark squares—double ports



The consistency of performance is best indicated by the fact that above 1,300,000 kva every operation fell in a narrow band between three and four cycles.

Conclusion

The multibreak interrupter follows logically the development of earlier oil-blast chambers and the superspeed impulse breaker. Proved by both laboratory and field tests, it makes available performance closely approaching the impulse designs for voltages 115 kv and above, but in circuit breakers of relatively conventional and inherently less costly design. It also affords a means of obtaining the advantages of this still higher speed operation on many breakers already in service when changing system conditions indicate such a need. Many existing circuit breakers may be modernized with these chambers to secure the superior performance demanded by a progressive and growing industry.

Acknowledgment

The authors thank and express their appreciation to the organizations of the American Gas and Electric Company, the Ohio Power Company, and the Southern California Edison Company, Ltd., whose courage, planning, and co-operation made these tests possible. It is a distinct tribute to the sound engineering and planning of the designers and operators of those systems, that system short-circuit tests involving short-circuit values of approximately 2,000,000 kva were made without delay, slight system disturbance, and no interference with customer's service. Tests of this kind are potent factors in the development of apparatus adequate for the present day high standards of system operation.

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7. CIRCUIT BREAKER FIELD TESTS ON STANDARD AND OIL-BLAST EXPLOSION CHAMBER OIL CIRCUIT BREAKERS, **R. M. Spurck** and **H. E. Strang.** AIEE TRANSACTIONS, volume 50, number 2, 1931, page 513.

Discussion

J. B. MacNeill (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The paper by Spurck and Strang and that by Sporn and St. Clair, both on the subject of high-voltage circuit interruption, are valuable additions to this art and demonstrate a high grade of ability in modern interrupters built along conventional lines.

It has been realized for some years that to obtain maximum interrupting speed on high-voltage circuits it is necessary to introduce multiple breaks. The idea of using groups of series interrupters isolated in the open position by a moving contact arm was developed several years ago.

Figure 1 of this discussion shows an early construction of this method. By it is obtained the necessary increase of total contact speed while maintaining reasonable velocities of the heavier moving parts. The follow-up action of the moving contact establishes a large open break after interruption has taken place. A construction having adequate 60-cycle and impulse voltage tests is thus secured with the required high speed of circuit interruption. Since the weight of moving contact material approaches that of an ordinary two-break device, there is no sacrifice in the closing speed necessary for synchronizing and high-speed reclosure.

An outstanding application of this principle was employed in the 287,000-volt breakers at Boulder Dam, which were covered in the paper by Wilcox and Leeds, presented at the Pasadena convention in 1936. Figure 2 shows the arrangement of contacts there used. With this construction circuit breaker times of well under three cycles have been obtained for the highest commercial voltages. Figure 3 shows an oscillogram of one-half a pole unit opening 2,900 amperes at 132 kv at a total time of 2.45 cycles on a 60-cycle circuit.

There has been some speculation as to the possibility of securing this type of performance in dead-tank structures at high voltages. Previous AIEE papers have referred to the unequal distribution of voltages between breaks, particularly with grounded short circuits. No particular means for taking care of this problem is evident in the design described by the authors. We would like to have their ideas as to the voltage distribution which takes place between the breaks with their designs under different conditions of short circuit. Is 90 per cent of the voltage across the ungrounded side in case of a grounded short circuit?

Means for securing suitable voltage distribution in such structures have been

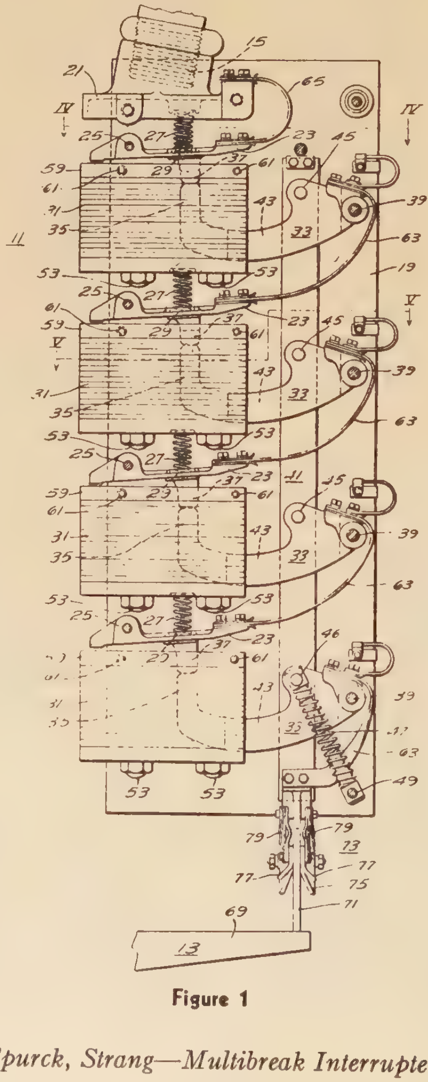

Figure 1

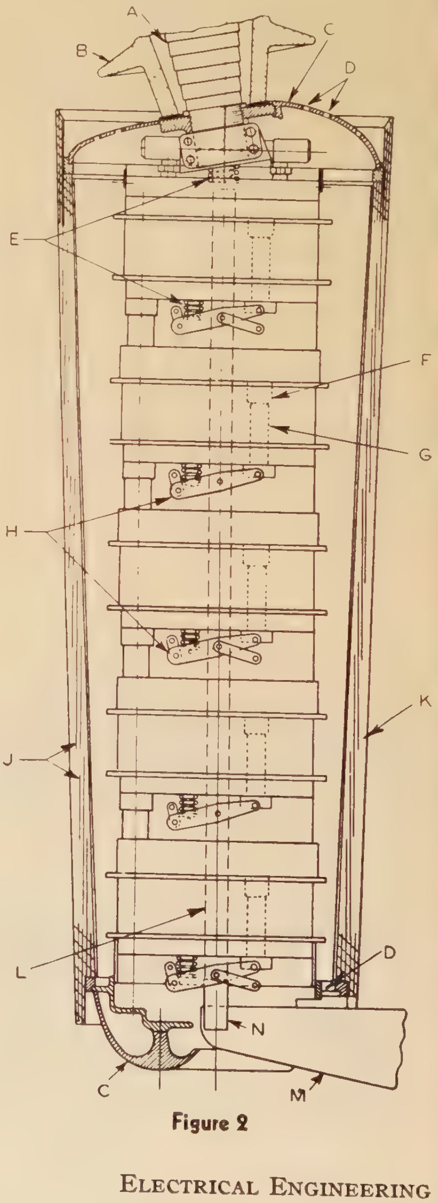

Figure 2

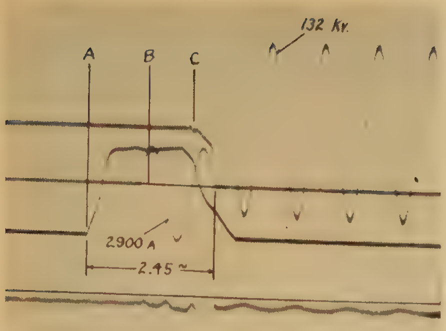

Figure 3

known for years and are useful in securing 60-cycle voltage tests and impulse tests as well as during arc interruption. Figure 4 shows a disclosure of the fundamental idea of electrostatic distribution between arcs as applied to oil circuit breakers made approximately ten years ago. The complete theory was covered in an AIEE paper by R. C. Van Sickle published in ELECTRICAL ENGINEERING for August 1937.

The papers by Sporn and St. Clair and by Spurck and Strang are noteworthy as showing variations of the construction referred to above and also applied to dead-tank circuit breakers. We hold that it is fortunate that the improved operation cited in the test results given in these papers has been obtained in conventional constructions which have a direct bearing on many existing American high-voltage stations, and which are usable in much old apparatus, as well as that offered for future sale. It would be unfortunate if ideas previously expressed to the effect that high-speed operation is obtainable only in porcelain structures should gain ground. The work of the past four years points to the conclusion that the highest grade of switchgear performance is obtainable, and with large factors of safety, in a standard dead-tank unit.

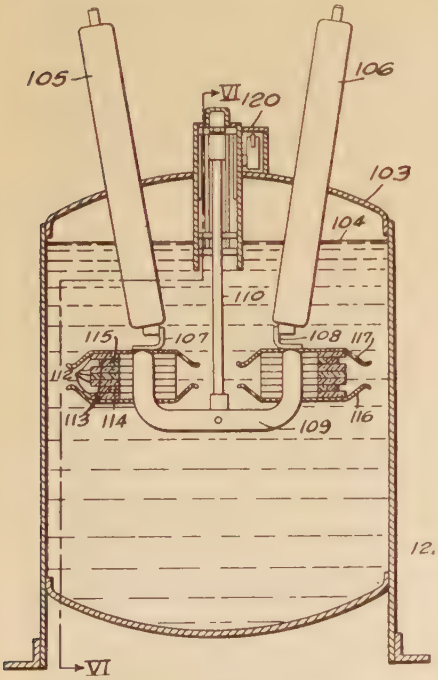

Figure 4

The writers speak of the 138-kv breaker as a four-break design and of the 230-kv type as a six-break design. They refer, in using these designations, to the number of points at which circuit rupture is accomplished. However, it seems to me that the 138-kv design has 10 breaks, consisting of 4 circuit-interruption breaks, 4 gas-generating breaks and, in addition, the 2 long isolating breaks. In the same way the 230-kv design has 14 breaks consisting of 6 circuit-interrupting breaks, 6 gas-generating breaks, and the 2 isolating breaks. Since the circuit presumably is interrupted in practically all cases before the isolating breaks get under way, there will be no contact depreciation at these points, but the other breaks share equally in contact burning and oil depreciation and we feel therefore that both the circuit-interrupting breaks and the gas-generating breaks should be recognized.

Both designs incorporate a number of breaks in a single container and reference is made in each paper to difficulties with this container during the process of development. Failure of the container places one-half of the pole unit out of service. Would not a rearrangement of the interrupters in individual containers, such as shown in the design of figure 2 give greater mechanical strength and greater assurance of operation in case of breakage of an individual unit?

W. F. Sims (Commonwealth Edison Company, Chicago, Ill.): The papers presented by Mr. Spurck and Mr. Sporn cover the development and test of an important advance in the art of arc interruption and bring to mind a few thoughts that should be of interest in this connection.

During the long period of financial stress to which we have all been subjected the manufacturers have gone steadily ahead with constructive research and development in bringing out improved devices of greater interrupting duty and shorter arcing time. They should be commended for their foresight in carrying on this work under adverse conditions, which insures to the utilities the availability of new equipment to meet the more severe and ever changing requirements. Because of this attitude on the part of the manufacturers we can have full confidence that new equipment will continue to be produced as required.

In connection with the tests on this equipment, it is a noteworthy fact that these two companies had such confidence in the soundness of the design and in the integrity of construction of their systems as to be willing to permit short circuits to be placed on their systems under maximum conditions. Much credit is due these companies for their courage and willingness to carry out these tests in the field under the conditions to be met in actual operation.

The high-power laboratories at the factories, which represent large investments on the part of the manufacturers, are of great value in the working out of new designs and in testing their component parts. However, it is not economically feasible to provide laboratories that would subject the equipment to the same conditions that would have to be met in service. The interests of both the manufacturers and the utilities are very greatly advanced because of the willingness of these companies to permit these field tests to be made upon their systems.

It is important to note that the manufacturers in their developments have designed these improved arc interrupting devices in such manner that they can be used to replace corresponding parts of older design and can be installed within the structures of existing equipment. This is an economic achievement which will save the utilities large investment expenditures when the breakers now on their systems become inadequate to meet the more severe conditions brought about by system growth.

E. E. George (Tennessee Electric Power Company, Chattanooga): One of the most interesting features of high-speed breakers associated with high-speed relays is the ease with which staged tests can be made on week days during peak load conditions at any point on the system. When making staged tests ten years ago it was frequently necessary to select an isolated corner of the transmission system, provide a special generating setup, change many relay settings, and schedule the tests between midnight and 5:00 a.m. on Sunday or Monday when the industrial load would be at a minimum. Even then power sales departments and customers' electricians needed considerable reassurance.

With eight-cycle breakers and high-speed relay, tests are now made satisfactorily during peak load periods at the heart of the system without disturbance to customers and without re-arrangement of system connections or generating setup.

H. A. Lott (Southern California Edison Company, Ltd., Los Angeles): Engineers of the Southern California Edison Company, Ltd., have been interested in the modernization of existing 220-kv breakers as an essential part of the program for continued improvement in continuity of service. The first step in the program of modernization was made in 1932, when six 220-kv breakers were rebuilt on the basis of 12 cycles, on a 50-cycle base. Subsequent development and experience resulted in revised specifications calling for eight-cycle interruption, whereas more recent development and experience indicated a still further reduction in over-all time of clearing not to exceed five cycles as being the probable practical limit for the clearance of short circuits by the addition of modern interrupters to existing breakers.

The modernization program has continued since 1932. At present, 62 out of a total of 103 220-kv breakers have been rebuilt to 12 cycles or better. The program has progressed at a conservative rate in order to take advantage of new developments, and also to receive some operating experience with higher speed clearances, which would tend to establish a practical balance between the added cost of still higher interrupting speeds and the necessity for such higher speeds.

The Southern California Edison 220-kv system is characterized by extensive high-voltage transmission lines. The generation is predominantly hydroelectric, with 399,000 kilowatts concentrated in the five Big Creek plants located 250 miles from the load center. The hydro generation is supplemented by 355,000 kilowatts of steam generation located at Long Beach, 25 miles from the load center. These two major plants, which are 275 miles apart, are interconnected with 825 circuit miles of 220,000-volt transmission line. This portion of the system, together with the seven step-down substations and 400,000 kvs of synchronous condenser capacity, must transmit and transform 85 per cent of all of the energy generated by the Edison system.

The importance of fast clearances on this system is evident when under maximum short-circuit conditions of $2^1/_4$ million kva an over-all clearance of five cycles is required in order to prevent instability following multiphase short circuits during heavy load conditions. During the past six years, 116 short circuits have been cleared from the 220-kv system. Four of the short circuits started multiphase, while 11 of the short circuits developed into multiphase after an average duration of about 15 cycles; the remainder were single conductor to ground short circuits. If it is possible to clear all faults in 12 cycles, we can expect to have two cases of instability each three years, based on the past six years experience, whereas clearances in the order of 5 to 8 cycles would be expected to eliminate most of the cases of instability caused by short circuits which start multiphase.

Since the program of rebuilding breakers was started, it has been found that the damage at the point of fault is now practically negligible, when the clearance is effected in 15 cycles or less. The damage at points of flashover is so slight that it is now necessary to climb towers and make a close inspection in order to locate the trouble. An effort is now being made to determine the approximate location of such faults by utilizing recorded values of ground current.

In order to assist in the development of high-speed interrupters, it was realized that it would be necessary to supplement factory tests, where certain limitations in both voltage and capacity exist, by field tests under actual operating conditions, where maximum short-circuit duties of $2^1/_4$ million kva were available. Accordingly, the first series of field tests at 220 kv were made at our Saugus substation in October of 1936, when a total of 15 short circuits, varying from 300,000 kva to 1,700,000 kva were made without indication of instability or without inconvenience to consumer's service. From these tests, it was evident that if the over-all time of clearance was in the order of five to eight cycles, similar tests could be carried to the maximum values of $2^1/_4$ million kva without instability or inconvenience to consumer's service.

Subsequent to the 1936 tests, the first series of tests on the "New Multibreak Interrupter" described in the paper presented by Messrs. R. M. Spurk and H. E. Strang, were made in April of 1937, with short circuits varying from 300,000 kva to 1,700,000 kva. These tests proved the electrical performance of the new interrupter, but indicated a mechanical weakness that could be readily overcome. The second series of tests on this type of interrupter was made in October of 1937, with the results as described by the authors.

During the tests at Saugus, the system generating capacity, interconnected during each test, was 560,000 kva; of which 360,000 kva was at Big Creek, 210 miles from the point of fault, and 200,000 kva was at Long Beach, 65 miles from the point of fault. Including the synchronous condenser capacity of 400,000 kva, which was in operation at the time of test, the total synchronous capacity was 960,000 kva.

The Saugus 220-kv construction is our standard 220 kv double-bus construction with two breakers, one to each bus for each position, which greatly facilitated the switching necessary to obtain the various values of short-circuit current. A complete duplicate opening and closing circuit for both the test and back-up breakers, together with the test relays, oscillograph, etc., were set up in a temporary relay house just outside the bus yard. A portable dark room was installed near the relay house to provide facilities for developing films between each test. The several values of short-circuit current were obtained by opening lines of different lengths from the load bus and closing them to the test bus at Saugus. The maximum values were obtained by paralleling the load bus and the test bus.

The test was completely planned and a printed program giving each step in the operating procedure was distributed to the system dispatchers, and all operators concerned in advance of the test. Telechron clocks were synchronized before the test started, and the 220-kv station operators were notified about five minutes prior to each test, of the exact time of each test. One man was selected to maintain all contact between the test location and the system load dispatchers, so that after each system setup had been completed, a time was selected and the short circuits applied without further instructions. As a result, the tests progressed rapidly. Four different line and bus arrangements were made to obtain the short-circuit-current values, and 15 short circuits were imposed and cleared between 9:15 a.m. and 2:00 p.m.

The results, from an operating standpoint, were ideal in every respect. There was no dip in system speed, and a maximum voltage dip of only 7 per cent was recorded under the most severe condition. There were no consumer complaints, since in every one of the 15 cases, the short circuit was cleared with but a barely perceptible flicker of consumer's lights. It was again established that short circuits would not impose an inconvenience to consumer's service if cleared by high-speed relay and breaker operation. The performance of the switch was such that following an inspection of the contacts, the breaker was placed in routine service without requiring any further adjustments.

The authors are to be congratulated for their presentation of such an interesting paper, marking another step toward better continuity of service through the medium of improvement in circuit breaker design.

A. C. Schwager (Pacific Electric Manufacturing Corporation, San Francisco, Calif.): It is gratifying to notice the improvement obtained with the fast-clearing circuit breaker described by the authors over the two-break oil-blast breaker. The reduction in opening time is accomplished mainly by the use of the multibreak principle which seems to become the conventional means among all manufacturers for obtaining fast interruption. For an analysis of the effectiveness of the device described it would be interesting to know the arcing times present during the interruptions listed in table II and the possible improvement in performance if potential grading had been used.

R. M. Spurck and **H. E. Strang:** We appreciate the constructive and interesting discussions presented on this paper. The discussions of Messrs. George Lott and Sims add materially to the paper and do not seem to require any further discussion from the authors. Mr. Lott's comments are of particular importance as they apply to the Southern California Edison System on which the 220-kv tests were made.

Messrs. MacNeill and Schwager ask about the potential distribution across the contacts. As stated in the paper, no means for grading the voltage across the various breaks was provided except that resulting from the normal arrangement of parts. The natural grading so obtained was so effective, as evidenced by the excellent performance of the breaker, that the additional application of artificial grading was not justified. In general, the arcing times obtained during the tests listed in table I were between one-half cycle and one cycle.

We emphasize that breakers with this type of interrupter are intended for five-cycle operation. Breakers for three-cycle operation at 287 kv, as used on the Boulder Dam, Los Angeles line, are of the impulse type described by Mr. D. C. Prince before the Institute in 1935. (D. C. Prince, "Circuit Breakers for Boulder Dam Line," AIEE Transactions, volume 54, 1935, page 366). In that paper, the results of various tests are listed. One test shows one-half of one pole of the breaker clearing 730 amperes at 264 kv in 2.45 cycles. That performance is much better than the performance shown on the oscillogram presented by Mr. MacNeill in his discussion, where one-half of a pole unit of a 287-kv breaker interrupted 2,990 amperes at 132 kv in 2.45 cycles. Even though the multibreak interrupter cleared the circuit in all cases substantially under its rating of five cycles, we have found no reason for departing from the impulse-type porcelain-clad breaker of the type used on the Boulder Dam, Los Angeles line when three-cycle operation at high voltage is required.

Some question has been raised on the number of breaks used. The text of the paper and the captions of the illustrations refer to the number of breaks per interrupter. Thus, if six-break interrupters are used as for the 220-kv tests, there are twelve breaks total in the two interrupters in addition to the isolating breaks.

Mr. MacNeill discusses the advantages of multibreak interrupters which do not require main moving contacts more complicated or heavier than those used in conventional two-break tank-type breakers. The multibreak interrupters described in our paper have such desirable features. Also, these interrupters have been designed with one housing surrounding a group of breaks rather with one housing for each break or pair of breaks in the interest of greater strength of the housing, simplicity of construction, and ease of housing removal for inspection.

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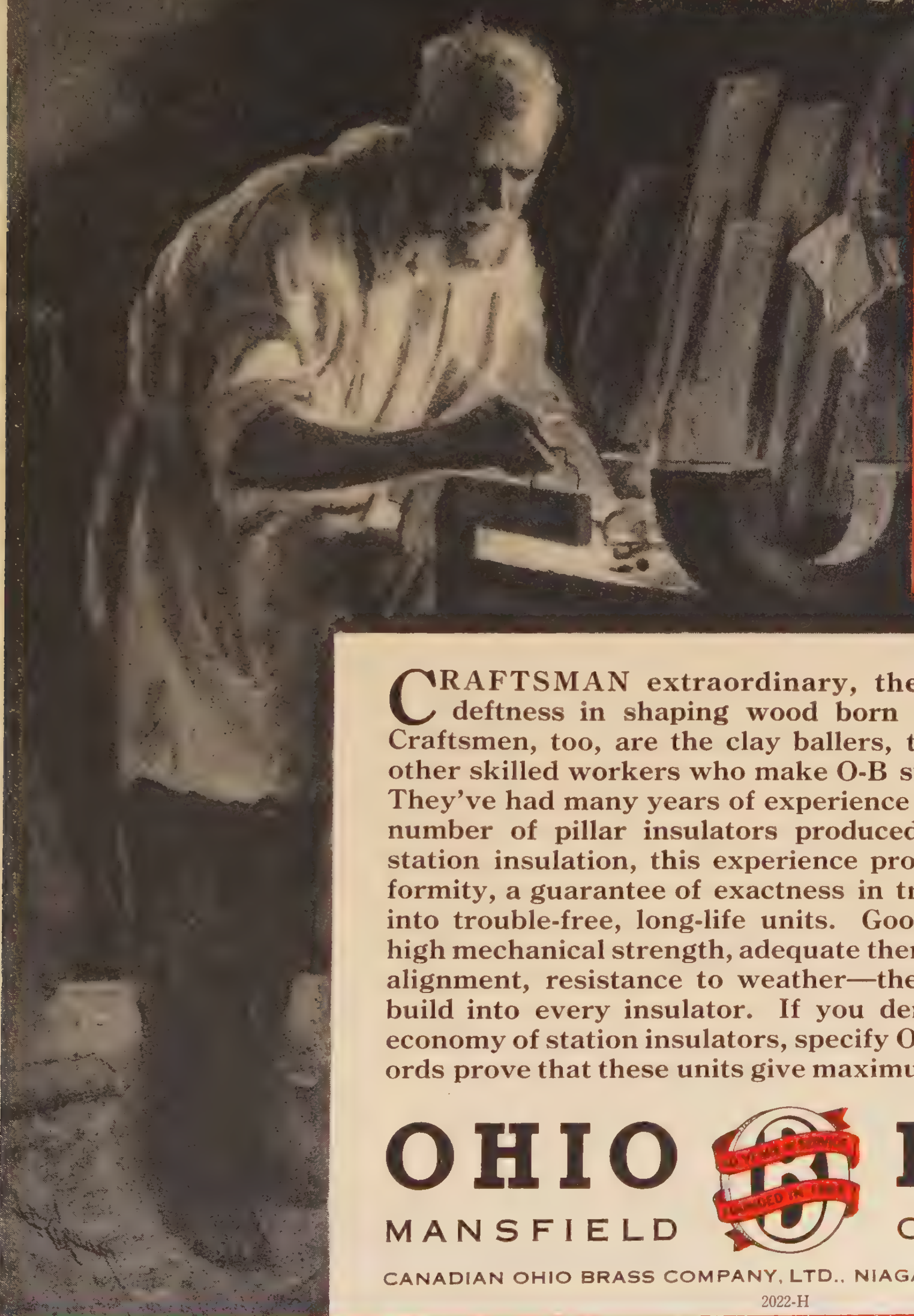

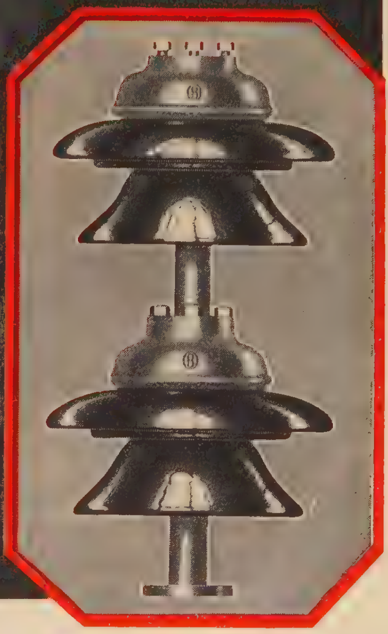

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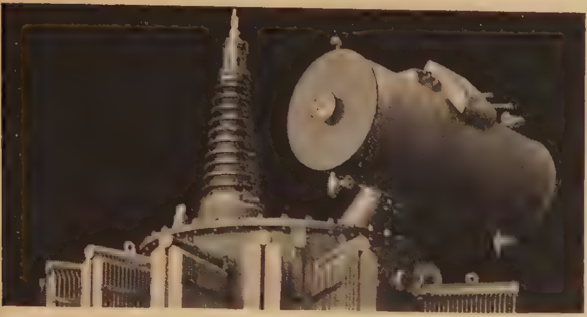

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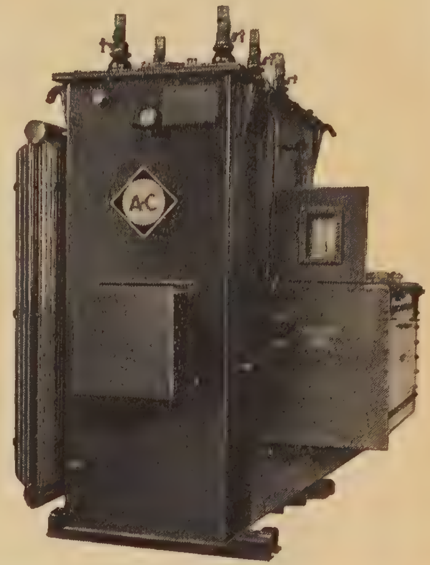

Smooth regulation of primary feeders pays a good return on your voltage regulator investment in terms of increased load and customer satisfaction. The smaller the size of step, the closer the voltage can be regulated . . . the smaller the voltage and kva to be handled by the tap-changing mechanism. You get better contact performance . . . smoother operation . . . less maintenance trouble and expense. For these advantages, informed engineers favor 5/8% Half-Cycling Step Regulators over other types. Send for Engineering Bulletin 1170-B.

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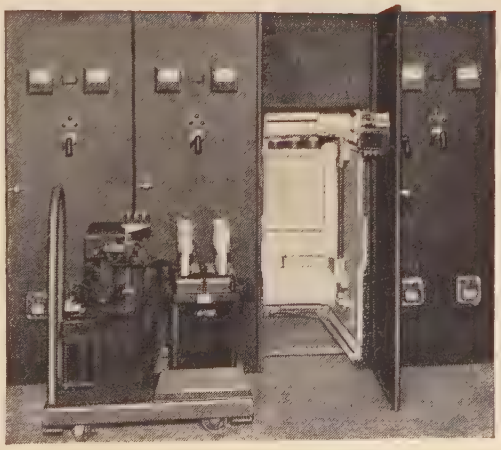

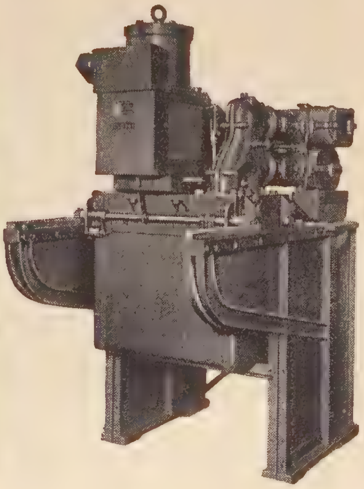

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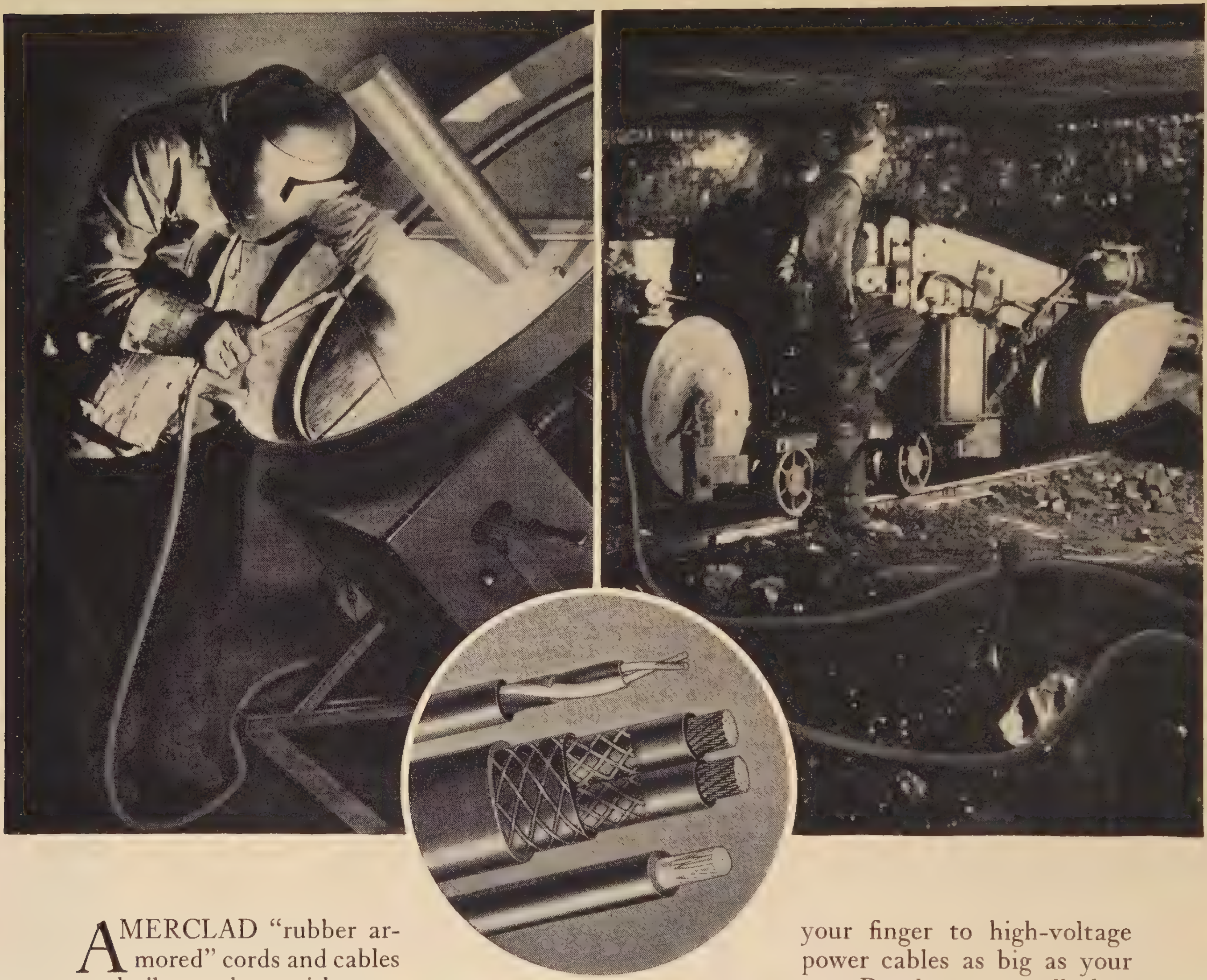

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Industrial Notes

Leads In Rural Electrification.—North Carolina now leads the south in number of customers being served by rural electric lines, with a total of 45,425 users on lines either built or authorized up to July 1, 1938, according to the North Carolina Department of Conservation and Development. In 1937 North Carolina ranked in fifth place in the U. S. in number of farms electrified. In the three years preceding July 1938, more than 7,000 miles of rural electrification lines have been completed and more than 1,000 miles were under construction or authorized. Of these lines, 6,467 miles were built or authorized by the public utility companies operating in that state, while 565 miles were built or authorized by municipalities; 1,151 miles were built or authorized by the Rural Electrification Administration.

Marine Order to Westinghouse.—The sale of nearly a million dollars worth of propulsion and other marine gear to the Standard Oil Company of New Jersey was effected recently by the Westinghouse Electric & Mfg. Co. This material will be used in the outfitting of a fleet of twelve new twin-screw oil tankers. These ships will be notable for their speed—18 knots trial speed when fully loaded. The tankers will be propelled by high pressure steam turbines developing 13,500 shaft horsepower. Each vessel will have an overall length of 551 feet and a cargo capacity of 145,000 barrels.

New Industrial Glass Division.—The Anchor Hocking Glass Corporation, Lancaster, Ohio, has established a new industrial division to cooperate with manufacturers in promoting the use of glass for many industrial purposes. In the electrical field the company is prepared to produce glass in practically all forms for insulating parts, meter covers and other uses.

General Electric Appointment.—O. H. Van Amberg, engineer of wiring systems for the General Electric construction materials division, Bridgeport, Conn., has been assigned to special duties in connection with all U. S. Government bureaus and Federal projects, and will henceforth make his headquarters in Washington, D. C.

Ohio Brass Appointment.—Claude R. Kingsbury has been appointed representative, with headquarters in Seattle, Wash., of the Ohio Brass Co., Mansfield, O. He succeeds J. W. Watkins, resigned. Mr. Kingsbury has been with Ohio Brass since 1927, first at the Barberton insulator plant, in charge of the electrical laboratory and more recently at the Mansfield plant engaged in street railway and trolley coach engineering.

New Fiber Glass Company.—The Owens-Illinois Glass Co. and Corning Glass Works have formed the Owens-Corning Fiberglas Corporation, which will produce a variety of products made from fiber glass.

The result of the extensive research facilities of these two companies, the products to be manufactured by the new corporation are said to promise revolutionary developments in many fields of insulation, construction and industrial design. Applications in the electrical industry are covered in an article "Fibrous Glass for Electrical Insulation," which appears in this issue, beginning on page 480.

Trade Literature

Voltage Regulators.—Bulletin 2326, 4 pp. Describes rocking contact voltage regulators for automatic control of small a-c and d-c generators. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Welding Accessories.—Bulletin 401, 36 pp. Describes arc welding electrodes and accessories, and outlines procedure for the welding of various metals. Lincoln Electric Co., 12818 Coit Road, Cleveland, O.

Zinc Castings.—Booklet, 24 pp. Describes and illustrates the use of zinc alloy die castings in industrial equipment. The New Jersey Zinc Co., 160 Front St., New York.

Sectionalizer.—Bulletin, 4 pp. Describes "Line-Arc" repeating sectionalizer for the protection of d-c sectionalized power circuits in mines and for protecting power feeders for cranes, crane runways, etc. The Electric Controller & Mfg. Co., Cleveland.

Industrial Vacuum Cleaners.—Bulletin A-303, 8 pp. Describes heavy-duty, industrial portable vacuum cleaning units. United States Hoffman Machinery Corp., 105 Fourth Ave., New York City.

Synchronizers.—Bulletin 1193, 8 pp. Describes the "Synchro-Operator" for automatically paralleling a-c generators, synchronous condensers, tie lines and frequency changers. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Magnetic Clutches.—Bulletin 225, 16 pp. Describes magnetic clutches and combination clutch brakes; applications are illustrated. Stearns Magnetic Mfg. Co., Milwaukee, Wis.

Laboratory-Industrial Equipment.—General Radio catalog "K," 216 pp. A comprehensive volume describing in detail, with prices, a wide line of industrial and laboratory apparatus. Industrial devices include Stroboscopes (for observing and measuring fast moving operations in slow motion); Sound level meters, analyzers, d-c amplifiers and Variacs (recently developed type of a-c voltage control). Other sections are devoted to Decade resistors, resistance units, volume controls, rheostat-potentiometers; Capacitors, air and mica capacitance standards, general purpose condensers; Bridges for measuring capacitance, power factor, inductance, resistance; Oscillators; Amplifiers; Meters, vacuum-tube and rectifier-type voltmeters, power-level indicators and others; Frequency measuring equipment, primary and secondary standards, etc.; Standard-signal generators; Parts and accessories, audio transformers, switches, dials and knobs, plugs and jacks, coil forms, chokes, relay racks. Reactance charts and decibel tables are included. General Radio Co., Cambridge, Mass.

Rectifiers.—Bulletin R-38, 8 pp. Describes recent developments in dry metallic rectifier construction, their application and performance. Rectifiers and filter circuits are discussed and typical ratings shown. New developments include heavy duty single stack rectifiers and forced draft cooled units. The B-L Electric Mfg. Co., 18th & Washington Ave., St. Louis, Mo.

Switchboards.—Bulletin 385, 8 pp. Describes "Vacu-Break" switchboards, constituting a more compact, modernized type of feeder distribution center and featuring quick-make and quick-break switching, with positive arc control. Bull Dog Electric Products Co., Detroit, Mich.

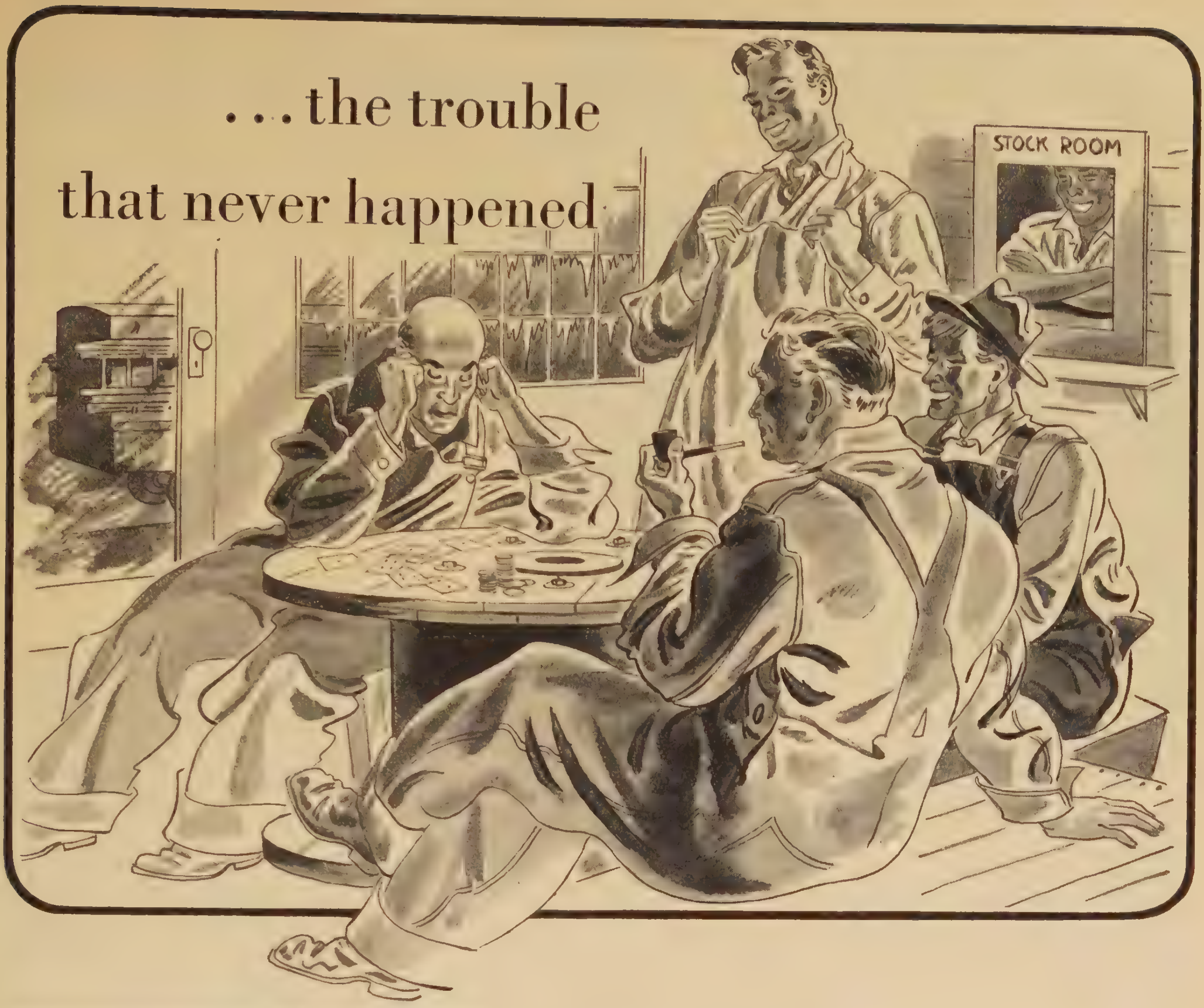
Guy Strands.—Bulletin E. D. 1686, 8 pp. Contains tabular information on the physical properties of guy strand, and notes on installation practices; includes a convenient, graphical method of determining the required strength of guys. Copperweld Steel Co., Glassport, Pa.

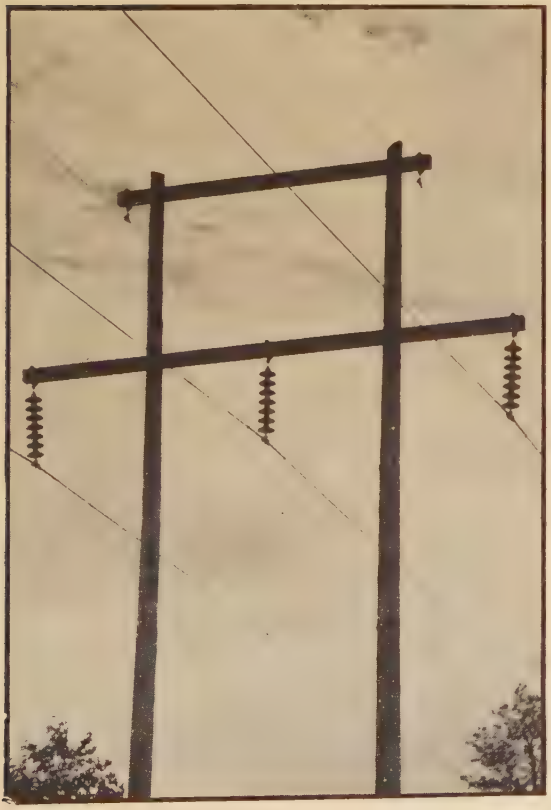
Insulation Testers.—Bulletin 405, 4 pp Describes type "OK" megohmmeters for insulation testing. The instruments are made up with either 220-volt or 500-volt d-c generators, and with a range of either 20 or 50 megohms. In addition, some of them are arranged with voltmeter scales so as to permit their use as a-c and d-c voltmeters. Herman H. Sticht & Co., 27 Park Place, New York City.

Potentiometer.—Cat. E33A (1), 12 pp. Describes a new Wenner potentiometer for the measurement of thermocouple and other voltages; range 0 to 0.11111 volt. Fully outlines the Wenner principle and its application; includes data about materials used and the reasons for their use, describing how thermoelectric forces within the instrument are suppressed and compensated for. Leeds & Northrup Co., 4962 Stenton Ave., Philadelphia, Pa.

Power Transformers.—Bulletin DD 211, 16 pp. Describes completely self-protecting power transformers designed to provide a better standard service through a lower first cost installation than the equivalent rating in a conventional substation. These transformers are available in 1000 kva, OISC, 3 phase, 60 cycles, 55° C. temperature rise, high voltage 13,200–13,860–12,540 F.C. delta, low voltage 4160 star, 4-wire. They incorporate such features as automatic tap changing under load equipment, low voltage switch, thermal protection, lightning protectors and metering. Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

. . . the trouble that never happened





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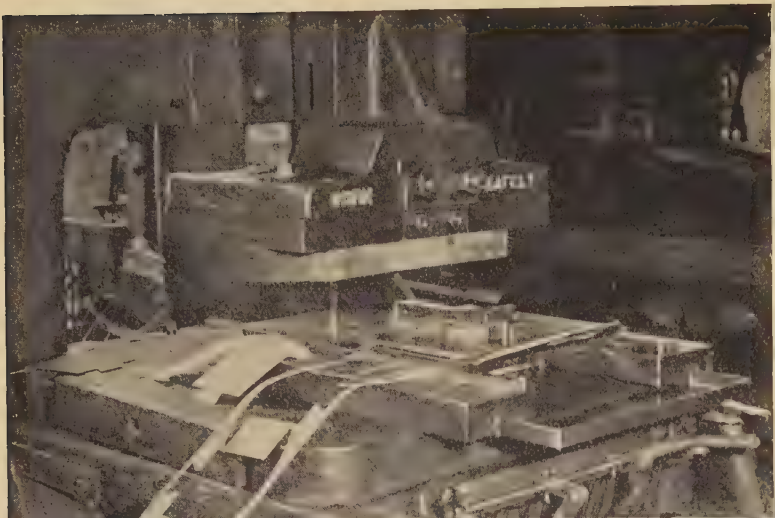

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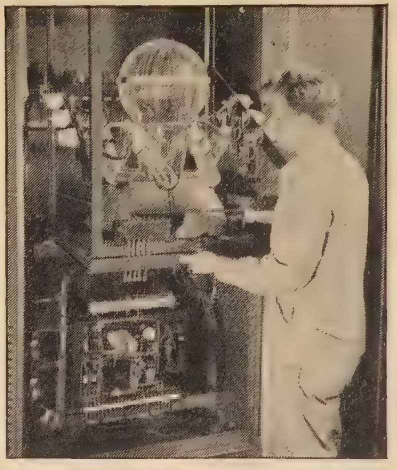
UNITED STATES STEEL

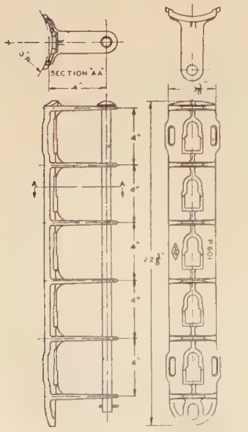
New Products

Arc Welder.—The new "Alternarc" machine, type W, is designed to supply for a-c welding purposes an "uninterrupted infinite variation of both current and voltage, with the proper voltage automatically supplied for each current," according to the manufacturer, the Electric Arc Cutting and Welding Company of Newark, N. J. This continuous constant-energy control is said to result in important economies in power consumption, and also in constant heat at the point of weld. Improvement in power factor also is claimed. The continuous rather than step-by-step control is effected through a control coil in the transformer and a movable portion of the transformer core. The illustration shows a 1,500-ampere assembly made up of three 500-ampere units.

Pothead.—The G & W Electric Specialty Co., Inc., Chicago, is offering a new pothead, type "T," outdoor capnut, single conductor, 7,500-volt, 250- and 500-ampere. Features include solderless clamp style internal and external connectors using a separate clamping plate which accommodates one range of conductor sizes in one position and another range of conductor sizes with the clamping plate reversed. The one set of connector parts takes care of an unusually large range of cable sizes. The external lug is designed so that the aerial conductor can be clamped vertically or horizontally by merely turning the clamp plate 90 degrees. The base sealing fitting is a stuffing box style, using oil-proof, molded rubber squeeze bushing. The hole in this bushing need only be varied for different cable diameters.

Small Mercury Arc Rectifier.—A small capacity, permanently evacuated rectifier unit using a glass heat-resistant bulb as a vacuum chamber, has been placed on the market by the rectifier division of the Allis-Chalmers Mfg. Co., Milwaukee, Wis. These new rectifier units require neither vacuum pumps, vacuum gauges, nor cooling water, being air-cooled by means of a small fan, and are available in sizes ranging from 50 kilowatts, 250 volts, to 300 kilowatts at 600 volts, or even higher voltages, furnished in factory wired and assembled cubicles. The necessary transformers and circuit breakers may be placed in any convenient location adjacent to the cubicle. For larger power requirements several units may be operated in parallel. They are especially adaptable to small traction systems and to industrial loads of moderate d-c power requirements. Where change-overs from direct to alternating current are being made, such rectifier units often permit economical continued use of existing d-c equipment.





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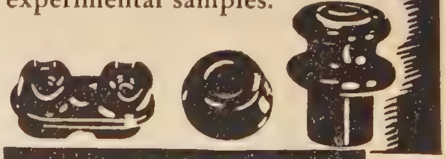

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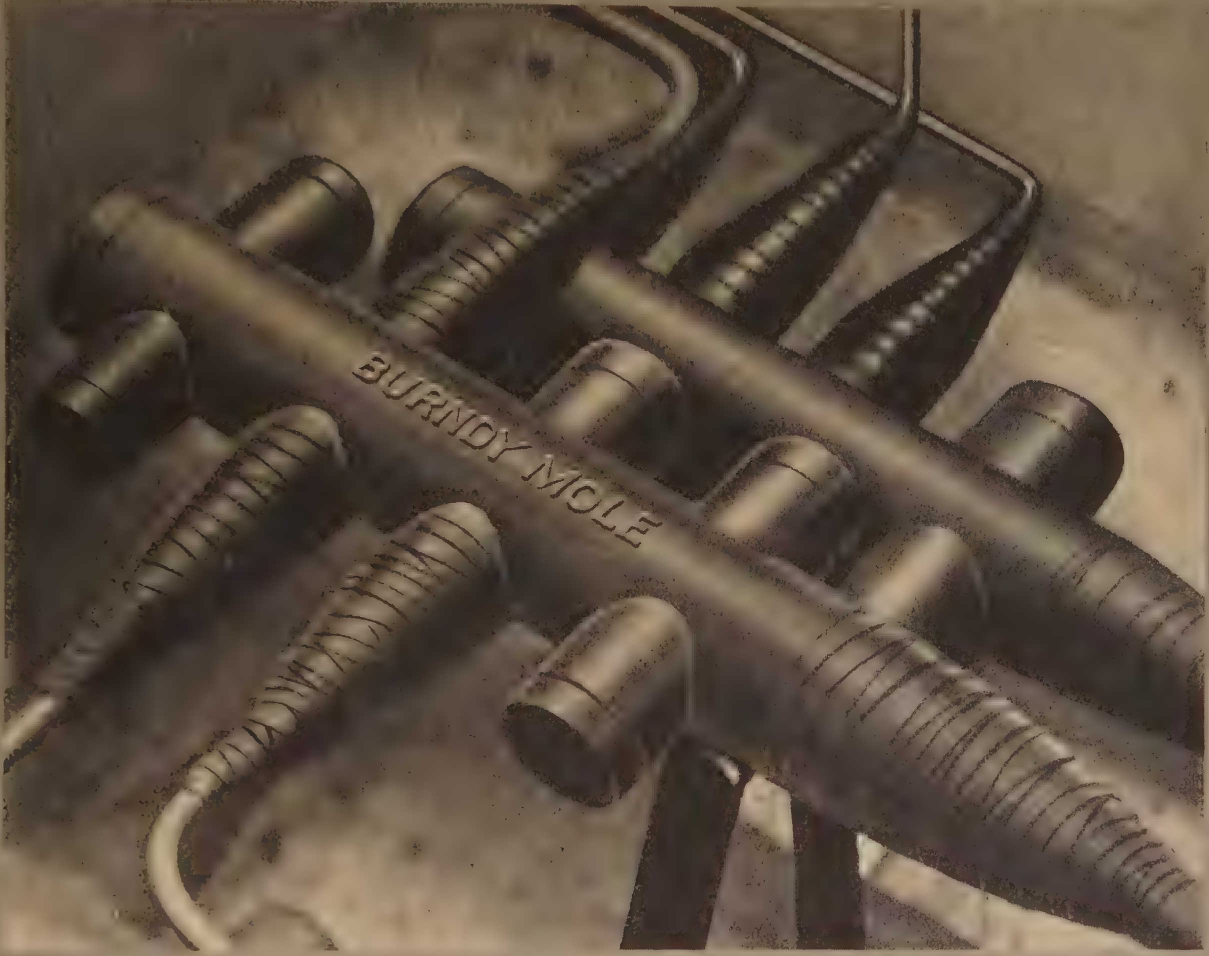
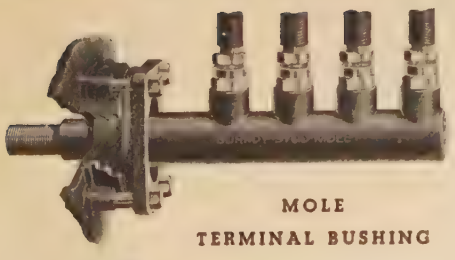
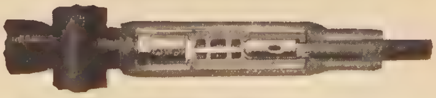


Horizontal mounting of Moles. Secondaries run from transformer in vault to Mole; services taken off at various outlets, One of many typical applications of the Mole.



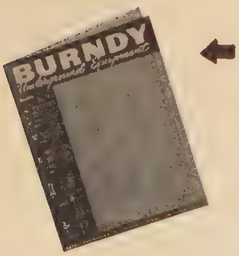
MOLE
TERMINAL BUSHING

← Left: Burndy Studmole, a combined insulated multiple terminal and bushing. Replaces porcelain bushings and gaskets on network protectors, seals out moisture and gas, provides many connections in limited space.



MOLIMITER

↑ Burndy Limiter Lug installed at Mole outlet and insulated by Asbestite shell and rubber jacket. Especially useful for fusing cables at network junction points.



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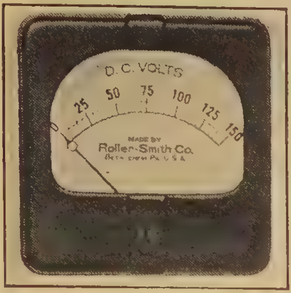

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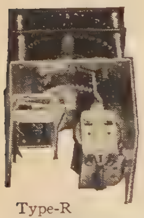

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B.S.E.E., 1936, 25, single, member Eta Kappa Nu. Student course large radio corp; one yr in research dept as test engr. Interested in radio, television or electronics research. E-358.

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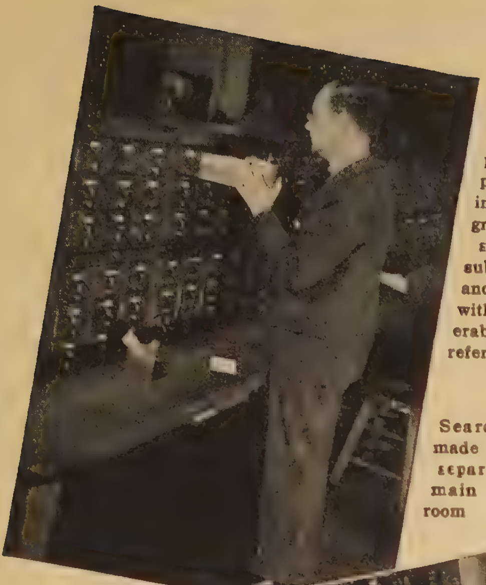

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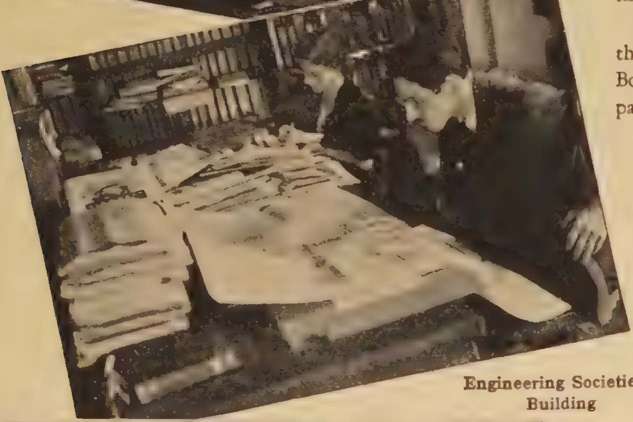

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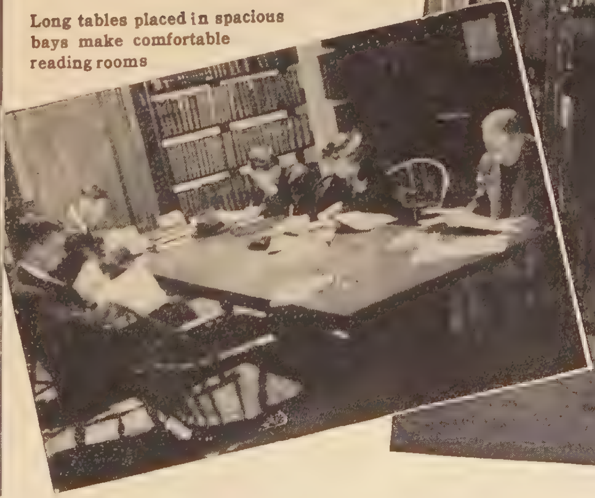

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INSULATING MATERIALS (*cont'd*)

Compounds
General Electric Co., Bridgeport, Conn.
Minerallac Electric Co., Chicago

Moulded
General Electric Co., Bridgeport, Conn.

Paper
General Electric Co., Bridgeport, Conn.

Porcelain
Universal Clay Products Co., Sandusky, O.

Tape, Friction
Minerallac Electric Co., Chicago
Okonite Company, The, Passaic, N. J.

Varnishes
General Electric Co., Bridgeport, Conn.
Minerallac Electric Co., Chicago

INSULATORS, PORCELAIN
General Electric Co., Schenectady, N. Y.
Ohio Brass Co., Mansfield, O.
Universal Clay Products Co., Sandusky, O.

LIGHTNING ARRESTERS
General Electric Co., Schenectady, N. Y.

LOAD RECORDERS—CONTROLLERS
Leeds & Northrup Co., Philadelphia

LOCOMOTIVES, ELECTRIC
Allis-Chalmers Mfg. Co., Milwaukee
General Electric Co., Schenectady, N. Y.

METERS, ELECTRICAL
(See INSTRUMENTS, ELECTRICAL)

MOTORS
(See GENERATORS AND MOTORS)

POLE LINE HARDWARE
Malleable Iron Fittings Co., Branford, Conn.
Ohio Brass Co., Mansfield, O.

POLE MOUNTS
Malleable Iron Fittings Co., Branford, Conn.

PORCELAIN, ELECTRIC
Universal Clay Products Co., Sandusky, O.

RECTIFIERS
Allis-Chalmers Mfg. Co., Milwaukee
General Electric Co., Schenectady, N. Y.

REGULATORS, VOLTAGE
Allis-Chalmers Mfg. Co., Milwaukee
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
Roller-Smith Co., New York

RELAYS
Dunn, Inc., Struthers, Philadelphia
General Electric Co., Schenectady, N. Y.
I-T-E Circuit Breaker Co., Philadelphia
Roller-Smith Co., New York
Weston Elec. Instrument Corp., Newark, N. J.

RESISTORS
Aerovox Corp., Brooklyn, N. Y.
Dunn, Inc., Struthers, Philadelphia
General Radio Co., Cambridge, Mass.
Ohmite Mfg. Co., Chicago

RHEOSTATS, LABORATORY
General Electric Co., Schenectady, N. Y.
Ohmite Mfg. Co., Chicago

SHEETS, ELECTRICAL
Carnegie-Illinois Steel Corp., Pittsburgh

SUB-STATIONS
Allis-Chalmers Mfg. Co., Milwaukee
General Electric Co., Schenectady, N. Y.

SURGE ABSORBERS
Ferranti Electric, Inc., New York

SWITCHBOARDS
Allis-Chalmers Mfg. Co., Milwaukee
General Electric Co., Schenectady, N. Y.
I-T-E Circuit Breaker Co., Philadelphia
Roller-Smith Co., New York

SWITCHES, AUTOMATIC TIME
General Electric Co., Schenectady, N. Y.
Minerallac Electric Co., Chicago

SWITCHES, DISCONNECT
General Electric Co., Schenectady, N. Y.
Roller-Smith Co., New York

SWITCHES, GENERATOR FIELD
I-T-E Circuit Breaker Co., Philadelphia

TOWERS, TRANSMISSION
American Bridge Co., Pittsburgh

TRANSFORMERS
Acme Elec. & Mfg. Co., Cuba, N. Y.
Allis-Chalmers Mfg. Co., Milwaukee
Ferranti Electric, Inc., New York
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.

TURBINE GENERATORS
Allis-Chalmers Mfg. Co., Milwaukee
General Electric Co., Schenectady, N. Y.

TURBINES
Allis-Chalmers Mfg. Co., Milwaukee
General Electric Co., Schenectady, N. Y.

WATCHES, STOP
Meylan, A. R. & J. E., New York

WELDERS, ARC
General Electric Co., Schenectady, N. Y.

WELDING WIRE
American Steel & Wire Co., Chicago
General Electric Co., Schenectady, N. Y.

WIRES AND CABLES

Aluminum
Aluminum Co. of America, Pittsburgh

Armored Cable
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Crescent Ins. Wire & Cable Co., Trenton, N. J
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.

Asbestos Covered
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
General Electric Co., Bridgeport, Conn.
Okonite Company, The, Passaic, N. J.

Bare Copper
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Copperweld Steel Co., Glassport, Pa.
Crescent Ins. Wire & Cable Co., Trenton, N. J.

Bronze
Copperweld Steel Co., Glassport, Pa.

Copper Covered Steel
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Copperweld Steel Co., Glassport, Pa.

Flexible Cord
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Electric Co., Schenectady, N. Y.
Okonite Company, The, Passaic, N. J.

Heavy Duty Cord
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Crescent Ins. Wire & Cable Co., Trenton, N. J.
Okonite Company, The, Passaic, N. J.

Lead Covered (Paper and Var. Cambric Ins.)
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.
Okonite-Callender Cable Co., Passaic, N. J.

Magnet
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Electric Co., Schenectady, N. Y.

Rubber Insulated
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.

Tree Wire
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Crescent Ins. Wire & Cable Co., Trenton, N. J.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.

Weatherproof
American Steel & Wire Co., Chicago
Anaconda Wire & Cable Co., New York
Crescent Ins. Wire & Cable Co., Trenton, N. J.
Copperweld Steel Co., Glassport, Pa.
General Electric Co., Schenectady, N. Y.
Okonite Company, The, Passaic, N. J.

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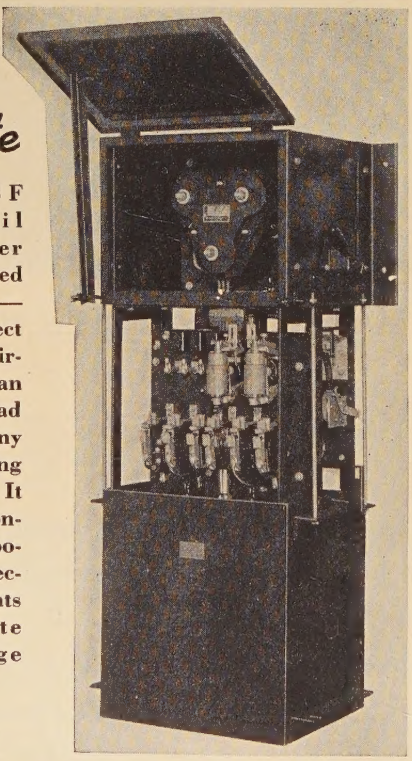

ROWAN CONTROL
THE ROWAN CONTROLLER CO., BALTIMORE, MD.

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Cambridge, Massachusetts

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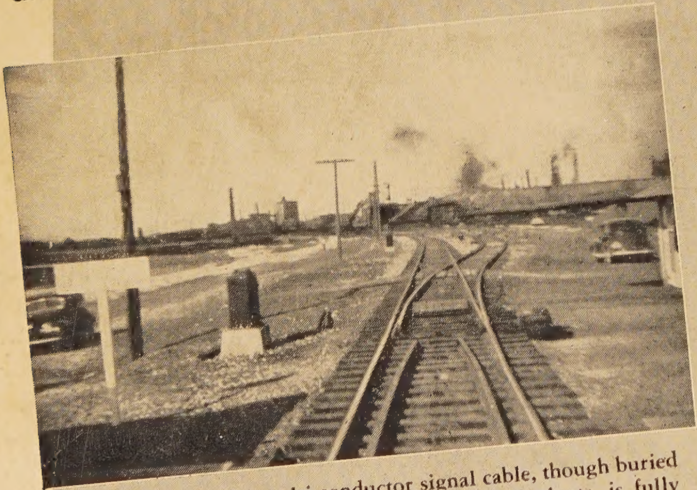

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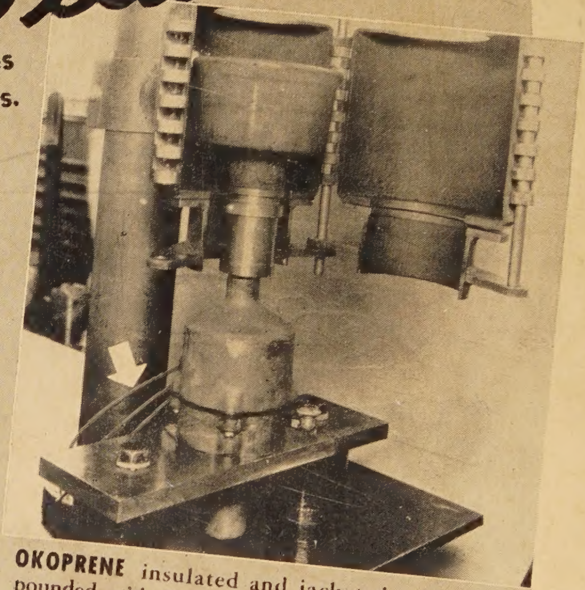

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